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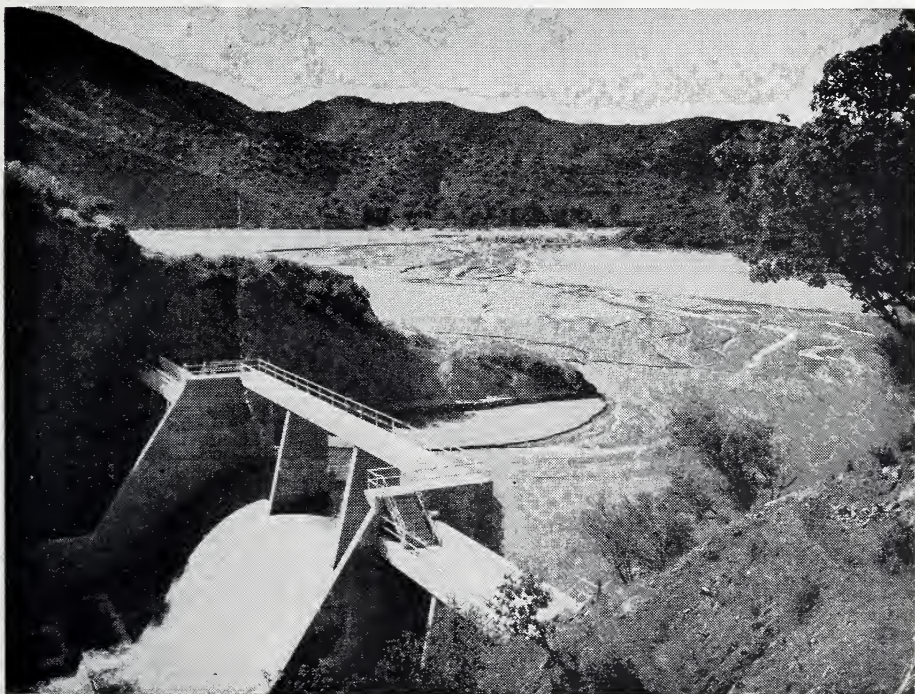
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The Control of Reservoir Silting

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UNITED STATES DEPARTMENT OF AGRICULTURE

ILLUSTRATION ON COVER

Mono Debris Dam above Gibraltar Reservoir, Near Santa Barbara, Calif. (FS-417101).

(Courtesy U. S. Forest Service.)

The Control of Reservoir Silting

By

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Soil Conservation Service



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FOREWORD

Water storage is a vital cog in the economy of war production in the United States. Our 9,000 larger dams and impounding reservoirs supply one-third of the Nation's electrical power, furnish water to areas where one-fifth of the Nation's people and about one-half of its war industry are located, and irrigate lands that produce about 5 percent of the annual value of its agricultural products. These dams and reservoirs have cost us nearly 5 billion dollars.

Many of the reservoirs that are vitally important to our war effort are losing 1, 2, 3, and even 5 percent of their capacity every year because of silting that results mainly from soil erosion on agricultural and range lands. In some exceptional cases, important reservoirs have filled up in from 1 to 5 years. Already, nearly 2 thousand smaller reservoirs have been filled to the top of the dam with the debris of erosion—mostly washed out of unprotected fields and pastures. The annual cost of reservoir silting is upwards of 50 million dollars.

During a 3-month period recently, silting in power storage reservoirs in certain Southern States reduced electrical production by 90 million kilowatt-hours. Water supply for many communities is in danger because their reservoirs are one-quarter or one-half filled with sediment at a time when population and industry, boosted by war demands, require two and three times the usual amount of water. In normal times, the answer to suddenly increased demands or to diminished supplies might be the construction of new reservoirs. During the war, however, we cannot spare the steel, the concrete, the labor, and the hundreds of manufactured items that go into new dams—except in the direst emergency. Somehow, we must get along with what we have.

This report has been prepared in an effort to meet the increasing needs and requests of reservoir owners for information on silting control. It is the first publication in this country to describe and appraise all of the known methods of control. Many of these methods could be put into immediate use. The publication especially emphasizes the measures of watershed control and soil conservation, however, for these are the only practical means by which we can permanently protect most of our reservoirs from untimely loss from silting. In our present economy, it is not generally practicable to clear a major reservoir of sediment once it has filled up. Moreover, when a reservoir is filled to the point where it has no further value for storage, not only is the investment lost, but the irreplaceable reservoir site is gone.

Other recent publications have emphasized that soil conservation must be adopted widely and rapidly to increase our production of essential food crops, meat, wool, poultry, eggs, fibers, and oils, without waste of soil, or ruin to the land. This publication shows that, in equal measure, soil conservation must be accelerated on our reservoir watersheds to protect these vital links in our war economy.

HUGH H. BENNETT,
Chief, Soil Conservation Service.

UNITED STATES DEPARTMENT OF AGRICULTURE

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The Control of Reservoir Silting¹

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CONTENTS

	Page		Page
Introduction.....	1	Methods of silting control—Continued.....	
Our reservoir developments.....	2	Control of sediment deposition.....	64
The problem of silting.....	6	Venting density currents.....	64
Previous investigations.....	8	Control of waste-water release.....	74
Studies by the Soil Conservation Service.....	9	Removal of sediment deposits.....	83
Effects of silting on different types of reservoirs.....	14	Excavation.....	84
The magnitude of silting damage.....	19	Dredging.....	86
Methods of silting control.....	21	Draining and flushing.....	94
Selection of the reservoir site.....	22	Flood sluicing.....	98
Design of the reservoir.....	24	Sluicing with controlled water.....	106
Development of a suitable capacity-watershed ratio.....	25	Sluicing with hydraulic and mechanical agitation.....	110
Raising the dam.....	29	Watershed erosion control.....	113
Installation of adequate outlet works.....	31	Sources of sediment.....	114
Control of sediment inflow.....	32	Effect of land use on erosion.....	118
Settling basins.....	32	Methods of erosion control.....	128
Vegetative screens.....	48	Efforts in watershed erosion control.....	147
Off-channel reservoirs.....	51	Planning for watershed control—an appraisal.....	153
Bypass canals and conduits.....	58	Literature cited.....	157

INTRODUCTION

This publication has been prepared in response to numerous requests from those concerned with water supply, irrigation, and power production for information on methods of controlling or reducing excessive silting in impounding reservoirs.² A few slight revisions and additions have been incorporated in this second edition.

This publication is essentially a digest of all the known methods of reservoir-silting control. It is based on a fairly complete review of a voluminous but widely scattered literature and on 10 years of field investigations of reservoir silting conducted by the Soil Conservation Service.

¹ This publication is based in part upon literature citations prepared by Official Project No. 165-2-97-23 "Compilation of Literature on Soil Conservation," Work Projects Administration for the City of New York, sponsored by the Soil Conservation Service. The help of this project is gratefully acknowledged. Among the many persons who have reviewed and offered helpful suggestions on this report, special acknowledgment is due to G. C. Dobson, Gordon Rittenhouse, Vito A. Vanoni, Hugh S. Bell, and G. R. Stewart.

² The term "impounding reservoir," as used in this publication, means the basin of an artificial lake formed by a dam for the storage of water and located on or immediately adjacent to a natural stream. Such reservoirs are often described as "storage reservoirs," but this term is also used in water-supply terminology to mean an artificial basin excavated in, or adjacent to, a city or other point of consumptive use for the storage and distribution of water pumped from a river or impounding reservoir. As such basins are excluded from consideration in this publication, impounding reservoir is used in preference to storage reservoir.

The methods of control are classified into six major categories. These groups are subdivided into specific methods. Each method is briefly described and a few selected examples are given of the application, costs, and results obtained. The appraisal at the end of each method description represents an attempt to present a generalization of the usefulness and applicability of the method. Many references to published literature are given in order that the reader so desiring may follow up the method in greater detail.

During the last four decades of peace, excepting the brief interlude of the first World War, the problem of reservoir silting was overcome largely by the construction of new and bigger reservoirs. As a Nation, we utilized our reservoir sites with abandon, much as we used our soil, turning from depleted or exhausted areas to fresh fields, with little view to the ultimate limits of the resources.

Now, in war, we are confronted with new circumstances. No longer can we continue widespread construction of new reservoirs. Only the most essential ones already started can be completed. Materials and labor must be used for war equipment. Thus, during this period more than ever before we must take all possible measures to conserve our existing reservoir developments.

Many of the methods described can be used in wartime without placing much, if any, extra drain on materials and labor, certainly not to the extent of building new dams. Special emphasis is given to those soil-conserving practices of watershed control that are a feature of good agriculture and a necessary part of our wartime food-production program.

OUR RESERVOIR DEVELOPMENTS

Impounding reservoirs are the most important of all types of water-utilization developments in the United States, both in terms of invested capital and in terms of the annual value of services. Impounding reservoirs have many uses, but their most nearly common purpose is equalization of water supply by storing the large flows of wet seasons for release during periods of drought and low runoff.

Water-supply and irrigation reservoirs, two of the most important classes, are built almost exclusively for storage. Power dams are constructed either to create a head of water for the generation of power or for the dual purpose of developing head and storing water to assure a more uniform rate of power production. In some drainage basins, impounding reservoirs have been built to equalize the flow at power dams farther downstream. Navigation reservoirs are usually built for the dual purpose of regulating the volume of flow in reaches of a river between reservoir pools and of developing deep-water channels with locks for floating ships through those sections of the stream that normally have high gradients or shallow depths. Flood-control reservoirs are built to hold back temporarily the excessive storm runoff that would be destructive to life and property in its path. Recreation reservoirs are built to bring swimming, fishing, and boating to lakeless areas. The uses of other classes of reservoirs, such as those supplying water for steam turbines, and those for fish hatcheries, wildlife sanctuaries, ice ponds, or debris traps, are obvious.

Dams to develop local power for gristmills, sawmills, and small factories have been constructed in the United States since colonial

days. Most of them created little or no storage, nor was storage very important, as their main purpose was to develop an artificial drop of water sufficient to propel the water wheels that drove the crude machinery of those early days.

By the first part of the nineteenth century the growth of urban areas on the eastern seaboard had already created serious problems of water supply. Water from local wells and streams became inadequate for domestic consumption, industry, and fire protection. To alleviate these conditions, numerous cities constructed impounding reservoirs in the middle years of the century (New York, 1837; Albany, 1852; Baltimore, 1862; Worcester, 1863; Providence, 1870), and were piping water many miles from these reservoirs to the consuming areas. In the West, San Francisco constructed its first water-supply reservoir in 1866.

In the 1830's and 1840's a number of impounding reservoirs were built, especially in New York and Ohio, to supply water for barge canals, then in their great period of expansion. Numerous impounding reservoirs to supply water for hydraulic mining of gold deposits were built in California from the 1850's into the 1870's.

The construction of sizable impounding reservoirs for irrigation in the Western States began in the middle 1880's, mainly in California, although some smaller reservoirs date back much farther. In Utah, the first irrigation reservoir was built in 1871 by the Mormons, pioneer irrigators among the western migrants.

Prior to 1900 few power dams would impound sufficient water to equalize effectively seasonal stream flow; however, the small pondage³ of water obtained at night permitted a higher rate of power production during the day at many dams.

Dams for navigation date back to the late 1700's in New England, and a few reservoirs were built in the middle 1800's to equalize stream flow as an aid to navigation.

It is probable that prior to 1900 not more than 2,000 dams and reservoirs had been built in this country, and that the investment in these did not exceed \$250,000,000. In November 1941 the national reservoir inventory of the Soil Conservation Service contained records of about 8,900 dams and reservoirs, exclusive of more than 3,800 listed farm ponds, conservation ponds, and low power dams. It is estimated that more than \$4,450,000,000 has been invested in these water-utilization developments, including those under construction during 1941 (fig. 1). This vast sum represents for the most part only the cost of the dams and reservoirs. Except for power plants built into the dams, it does not include dependent developments, such as water-filtration plants, irrigation canals, and power transmission lines.

Since 1930 there has been a sharp increase in the rate of construction of impounding reservoirs. The 72 largest reservoirs under construction during 1941 will cost, when completed, not less than 1 billion dollars. This construction reached a climax for the time being in 1942, only because of the growing shortage of materials and labor arising from the armament program.

³ In the terminology of water-power engineering, pondage is the holding back and later releasing of water at a dam to equalize daily or weekly flows or to meet variations in power demand (load). Storage is the impoundment of large amounts of water to equalize seasonal or yearly fluctuations of river flow.

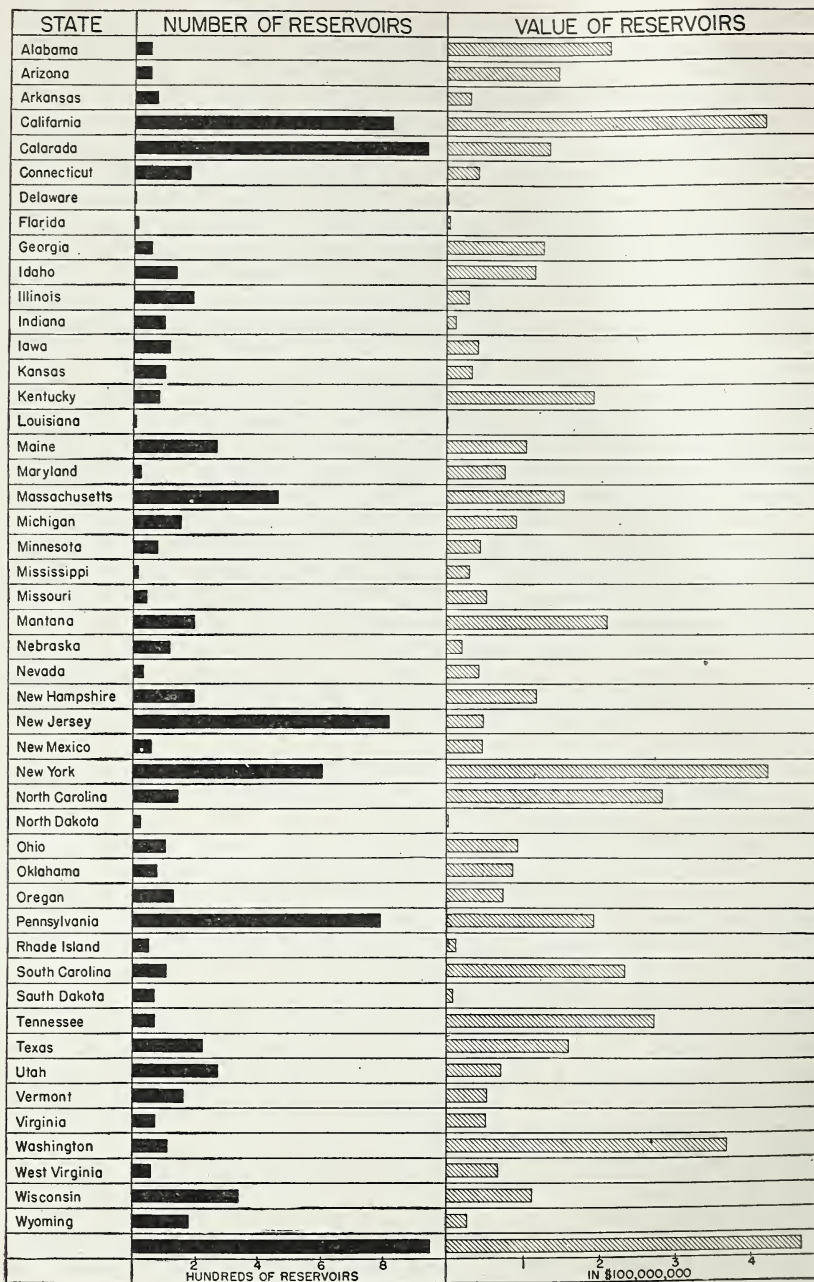


FIGURE 1.—Distribution of reservoirs in the United States. The bars in the lowest line represent the number of reservoirs in thousands and the value in billions of dollars for the entire country.

Although inventory data on older dams and reservoirs of the United States are still far from complete, it is possible to indicate the order of magnitude of investments in and services rendered by all the major classes of reservoirs. Power dams, numbering about 3,000, exclusive of low channel structures, constitute the largest class. The power plants at these dams generated approximately 47,750,000,000 kilowatt-hours of electrical energy during 1940, which was about 33 percent of the total electrical energy produced in this country. The cost of these dams, including the reservoir basins and power plants, was approximately \$2,850,000,000, or about 64 percent of the total national investment in dams and reservoirs.

The value of power dams is dependent, in varying degrees, on the amount of reservoir storage created. Power dams on larger rivers that have relatively uniform flow, such as those coming from lake and forested regions in New England, the upper Mississippi Valley, and the Cascade Mountains, may have little or no storage (although usually some pondage) value. On the other hand, power dams on streams in the southern Piedmont, Texas, California, and like areas of variable stream flow may be valued in large measure by the storage capacity they have available for equalizing stream flow. This is to say, if the dam created the same head but no storage, the average annual value of electricity produced might be only 10, 20, or 50 percent of that which can be developed with stream-regulating storage. The difference depends on the quantity and value of primary power production relative to secondary power. (See pp. 14-15.)

Water-supply reservoirs are the second largest group, with more than 2,700 dams having been constructed for public or industrial water supply at an estimated cost of more than \$566,500,000, exclusive of water works and distribution lines. A large part of the public water supply of the United States comes from impounding reservoirs. Many of the great metropolitan areas, including New York, Boston, Baltimore, Birmingham, Dallas, Denver, Seattle, San Francisco, and Los Angeles, depend wholly, or in large part, on reservoir systems. It is estimated that about 26,000,000 persons, or 20 percent of the entire population of the United States, obtain their domestic water from these reservoirs. The industries dependent on these reservoirs constitute such a large part of our whole industrial machine that sudden destruction of the reservoirs would paralyze production.

More than 1,800 reservoirs for storage of irrigation water have been constructed in the Western States, at an estimated cost of \$395,000,000. The agricultural products and livestock produced by the land dependent on these reservoirs are valued at an estimated \$250,000,000 annually, which is nearly 5 percent of the normal total annual value of the agricultural products of the United States. This, however, is hardly a measure of the value of these reservoirs, for the whole economic and social life of the Western States hinges in large measure on them. The value of land and developments dependent upon irrigation reservoirs exceeds by many times the cost of these structures, but these values can be maintained only so long as reservoir storage is available.

In recent years, and especially in the last decade, a large number of reservoirs have been built solely for boating, swimming, fishing, and

other recreational pursuits. It is estimated that there are now more than 1,200 sizable recreation reservoirs in the country, and that these have cost approximately \$67,500,000. Probably 5,000,000 persons, or 4 percent of the Nation's population, are normally using them.

More than 135 reservoirs have now been built primarily for flood control, at an estimated cost of \$555,000,000. Many additional reservoirs whose primary purpose is to develop power, irrigation, or water supply, also were designed to provide extra storage for flood control. It is estimated that reservoirs afford flood-control protection to about 6 million persons and to property and other wealth of inestimable value.

In deriving these estimates, an attempt has been made to proportion the cost of multiple-purpose reservoirs, wherever possible, among their several uses. Where this could not be done satisfactorily, the cost was included in that group which appears to represent the dominant use.

THE PROBLEM OF SILTING

Among the more important problems in the development and maintenance of impounding reservoirs is the loss of storage capacity by silting. Reservoir silting results from the deposition of stream-borne soil waste or sediment when the transporting power of the stream is suddenly diminished by flowing into the quiet impounded waters of a reservoir.

All streams transport some sediment and always have. Any lake basin into which streams flow will fill up with sediment in the course of time. It has been said that the history of a lake is the history of its death. Reservoir silting is today a serious problem, not just because sediment is deposited, but because it is deposited in such quantities as to cause serious economic and social losses to this generation and the next. The primary cause of this condition is accelerated soil erosion.

Under primeval conditions, before settlement by white men, a large part of the United States east of the 100th meridian was blanketed by dense forests or thick, tall grass. The mellow, permeable soils were firmly held by roots or covered by decaying litter of the forest. They were effectively insulated against removal by surface runoff. To be sure, occasional fires, animal trails, landslides, and other disturbances exposed some soil to washing. Unprotected stream banks must have existed, as the geological record shows countless migrations of rivers across their valleys and back again. Actual records of stream load are obviously unavailable for presettlement years, but many historical accounts indicate that, when first observed by white men, streams ran virtually clear, even at high water. Plain logic will lead to the conclusion that if former sources of sediment still exist, as they must for the most part, the addition of the enormous burden washed from tilled fields and burned-over forests has greatly increased the annual sediment load of the streams. This logic is confirmed by measurements of sedimentation in stream channels and on alluvial flood plains, where it has been found that rates of alluviation or sedimentation are many times those of the preagricultural era (65).⁴

⁴ Italic numbers in parentheses refer to Literature Cited, p. 157.

Even west of the 100th meridian, where streams have always carried much larger sediment loads than those in the East, various kinds of evidence indicate that rates of erosion and sediment production are definitely greater today than formerly. The increased amount of sediment is coming mainly from deeply incised, rapidly developing, and widely spreading channels (valley trenches, arroyos, gullies) in alluvium-filled valleys, and from surface wash and gullying on grass-depleted slopes laid bare by the grazing of too many domestic animals.

The rapid depletion of reservoir storage capacity resulting from soil erosion causes an annual damage of many millions of dollars, when measured simply by depreciation in investment. Reservoir sites must be valued as natural resources, however, apart from the capital expenditure for their development. They are just as certainly limited in number as are resources such as coal, oil, or iron limited in amount; hence, they may be just as definitely appraised as resources apart from their future development cost.

The regulated consumption of any natural resource for the maximum benefit of all is to be encouraged; its uncontrolled waste must be condemned. The consumption of a reservoir site begins when a dam is built; for even under geologic norms of erosion, the lake so impounded will fill up in time. The waste of this site begins when the reservoir located there is allowed to fill up at a rate that will make it useless in one or a few generations, even though the development can more than amortize itself financially in this short time.

In 1936, J. C. Stevens, in an article (*113, pp. 208-209*) based on his report on the silt problem to the Special Committee on Irrigation Hydraulics of the American Society of Civil Engineers, depicted the problem of reservoir silting in words that cannot be lightly dismissed, or scarcely made more forceful, as follows:

The construction of large storage reservoirs on some of the silt-laden streams of the West has focused attention on the part sedimentation will play in the future history of Western civilization.

An empire exists below the storage reservoir that has been created by the Elephant Butte Dam, on the Rio Grande, in New Mexico. The land is phenomenally productive. This region embraces a substantial unit of civilization the very existence of which hangs upon the integrity of a storage reservoir to impound and deliver the water so vitally necessary to life.

The reservoir created by Elephant Butte Dam is slowly being deprived of its ability to store water. Silt is being deposited at an average rate of 20,000 acre-feet per year. Its original capacity will be so depleted in two or three generations that the civilization now dependent upon it will have to seek other sources of water supply and storage.

Fortunately, sites are available where other reservoirs may be constructed; and, after these are gone, others will doubtless be found. Furthermore, the present dam could be raised to increase its storage capacity; but what of the ultimate future, when all available storage sites have been exhausted? Must those now fertile areas revert, ultimately, to the sage-brush and the cactus? Will sedimentation, that made possible this vibrant civilization, ultimately sound its death knell? How long can this episode in the annals of civilization continue and what can man do to prolong its existence?

The Boulder Dam, in the Colorado River, will create the largest storage reservoir in the world. Upon it will depend not only the security of the entire Imperial Valley against damages from floods, and the irrigation of millions of acres of land, but also the domestic and irrigation supply for the metropolitan district of Southern California. The ability to furnish power to the people in seven States also hinges upon its functioning. Unless remedial measures are adopted, this reservoir will become virtually useless, by reason of silt deposits, before the passing of the fifth generation.

Fortunately, as on the Rio Grande, a number of other storage sites are available on the Colorado River. Ultimately, however, within some definite number of generations, the fact must be faced that all these reservoirs will have become useless for storage purposes. The dependent peoples must then be reduced to those that can subsist on the areas which the unconserved flow of the river will irrigate.

It is not the writer's intention to paint a dark picture, but rather to stimulate a more intensive study and an intelligent research that will ultimately effect a practical solution of this problem. The menace exists; it is real; and unless something constructive can be evolved, civilization in these regions must eventually decline. It is unfair to sit smugly complacent and to pass this problem flippantly on to future generations. The engineer should be equal to the task of finding a solution, but it will take many years of experimentation and study, and he should be at the task, amply financed.

PREVIOUS INVESTIGATIONS

Ill effects from reservoir silting were experienced within a few years of the beginning of reservoir storage in this country. Baltimore, Md., was excavating sediment from its water-supply reservoir, Lake Roland, in 1872.⁵ In that year, the reservoir's capacity was increased more than 3,000,000 gallons by dredging, at a cost of nearly \$3,500. In 1877 (1) Reading, Pa., was excavating one of its water-supply reservoirs. In 1892, Altoona, Pa., found it necessary to excavate sediment from its Kittanning Reservoir, after it had been in service only 5 years (2).

Engineering consideration of the silting problem in reservoirs of the Southwest goes back at least as far as 1889. Rather extensive studies of probable rates of silting were made in connection with the development of several of the larger irrigation reservoirs financed by the Federal Government, especially Elephant Butte Reservoir (53), Roosevelt Reservoir (42), and San Carlos Reservoir (123). Agencies that participated in these studies included the United States Geological Survey, Bureau of Reclamation, International Boundary Commission, Office of Indian Affairs, and the Corps of Engineers, United States Army.

The first noteworthy survey in this country to determine the rate of sedimentation appears to have been that made on Sweetwater Reservoir, 12 miles southeast of San Diego, Calif., in 1895, 7 years after the reservoir was completed for irrigation storage (108). Prior to the completion of the old Austin Dam on the Colorado River of Texas in 1893 cross sections were established above it in anticipation of heavy silting. Remeasurement of these sections in February 1900 by the late Dean T. U. Taylor disclosed the then astonishing fact that the reservoir had lost 48 percent of its capacity in 6¾ years (116).

Baltimore's survey of its Loch Raven water-supply reservoir in 1900 disclosed a capacity loss of 85 percent in the 20 years since it was constructed in 1880, even though dredging had been started in 1896 (133). The first of several sedimentation surveys of Lake Chabot, now a part of the East Bay Municipal Utilities District water-supply system furnishing water to Oakland and adjacent communities in California, was made in 1900, 25 years after storage began (28).

⁵ BALTIMORE WATER BOARD. WATER ENGINEERS REPORT, 1872. Ann. Rpt. Water Dept., Baltimore, Md., pp. 53-97. 1873.

The first of several surveys of Lake McMillan on the Pecos River was made in 1910 (102); of Zuni Reservoir, Black Rock, N. Mex., the same year (102), and the Elephant Butte Reservoir on the Rio Grande in 1916 (113). Results of studies of reservoir silting in Texas made during the 1920's by the Division of Irrigation, Soil Conservation Service (formerly of the Bureau of Agricultural Engineering), in cooperation with the Texas Board of Water Engineers, were described by Faris (51) in 1933.

Taylor's publication "Siltng of Reservoirs" (117) in 1930 was a notable contribution to the literature, as it described most of the sedimentation surveys made up to that time, including several not previously reported. Prior to 1934, sedimentation surveys of varying degrees of accuracy had been made on 40-odd reservoirs in this country. Data on most of these surveys are contained in publications by Eakin (45, pp. 9-26) and Stevens (113, pp. 209-218).

Although a rather widely scattered, if not too complete, literature on silting has been available for 30 or 40 years, the problem has been very frequently ignored by designers, owners, and operators of reservoirs. Examination of a number of textbooks on water-works engineering written during the past 10 years, reveals only a cursory treatment of the problem. There is almost a total lack of literature on the effects of silting on hydroelectric power developments in this country. The relation of the problem to irrigation has been more intensively studied for the obvious reason that so many streams in the regions that require irrigation carry such heavy sediment burdens.

Perhaps the main reason for this apathy is the fact that not many of our larger and more widely known reservoirs are more than 40 years old, and few thus far have become useless. In other words, the cumulative effect of silting has not been rapid enough to force this problem into general prominence. The case closely parallels that of the recognition of soil erosion and its effects, a phenomenon to which the silting problem is intimately related. Since the days of Washington and Jefferson a few outstanding agriculturalists have expressed alarm over the ravages caused by soil washing from farm fields, but apathy both on the part of the public, and among leaders of social, agricultural, and political life in America was the prevalent state of affairs until most of the good land had been homesteaded and pressure on the older land began to increase about 25 years ago.

The inescapable evidences of wastage by soil erosion, spread before the traveler's eye from coast to coast, will inevitably be paralleled during the next few generations by the spectacle of vast tracts of soil waste behind great dams where once water was stored.

STUDIES BY THE SOIL CONSERVATION SERVICE

In 1935 Congress created the Soil Conservation Service as a permanent agency of the United States Department of Agriculture "to provide permanently for the control and prevention of soil erosion and thereby to preserve natural resources, control floods, *prevent impairment of reservoirs*, * * *" (122). To comply with this directive the Soil Conservation Service established in its Office of Research a section for sedimentation studies to determine (1) the character and extent of reservoir silting and other downstream dam-

ages that result from deposition of soil washed from upland slopes, and (2) the nature and location of control measures required to ameliorate these damages.

Progress made thus far in studying the problem of reservoir silting includes (1) an inventory of pertinent data on all American reservoirs, (2) detailed sedimentation surveys of approximately 150 representative reservoirs, and reconnaissance surveys of approximately 250 others, or, including surveys made by other agencies, the collection of data on silting in more than 450 reservoirs in 36 States, (3) determination of the physical and economic effects of silting on various types of reservoirs, (4) development of methods for determining the sources of sediment that cause reservoir silting, and (5) a preliminary analysis of the known methods of reservoir-silting control.

Although the nature, causes, and effects of reservoir silting are now becoming fairly well understood, there is a continuing need for investigation of silting control in specific reservoirs, which have a variety of individual and complex problems. A first requisite of control is to determine the character and rate of silting in the particular reservoir.

A reconnaissance-type survey has been developed as a means of ascertaining the approximate extent of reservoir-capacity loss and of determining whether a more detailed survey is needed. It consists of measuring the thickness of sediment at from 15 to 100 or more well-distributed locations in a reservoir by means of a measuring device known as the spud⁶ (figs. 2 and 3).

In operation the spud is dropped or thrown vertically from the side of a boat, and the attached rope is played out through the hands with only enough grip maintained to keep the spud in a vertical position when it hits the deposits. In sediment that has never been exposed to air, the spud, because of its weight, seldom fails to penetrate entirely through the deposit into old soil, even where the sediment depth is several feet greater than the length of the spud. When the spud is pulled up slowly through the water a sample of mud or underlying soil is retained in each groove of "cup" that had penetrated. Tests based on comparison, with original bottom profiles have shown that these samples come from the point at which each particular groove came to rest when the spud's downward motion stopped.

The successful use of the spud depends, first, on whether it penetrates through the reservoir deposits into the underlying material, and secondly, on the ability of the operator to distinguish the sediment from the underlying soil by color, texture, and other physical characteristics. Experience, involving tens of thousands of measurements, has shown that in most reservoirs less than half full of sediment, spudding is successful in 90 to 95 percent of all attempts. In reservoirs where measurements can be made successfully with the spud over most of the lake's basin, the ratio of sediment volume to the

⁶ The spud is a case-hardened or well-tempered steel rod, similar to axle shafting, into which encircling triangular grooves have been machined at intervals of one-tenth of a foot along its length. Each groove tapers outward from a maximum depth of one-quarter of an inch to zero at the rim of the groove one-tenth foot above, forming a series of horizontal shelves when the rod is held upright. Spuds of different dimensions have been used. The latest design is a sectional spud, shown in figure 2, consisting of five lengths of rod, each approximately 3 feet long, with sharp and blunt points. The sections contain threaded holes in their ends and are fastened together with dowel pins. When all sections are joined, this spud is approximately 16 feet long and weighs about 38 pounds. It may also be used in 6- and 9-foot lengths. Specifications can be obtained from the Sedimentation Section, Soil Conservation Service, Washington 25, D. C.

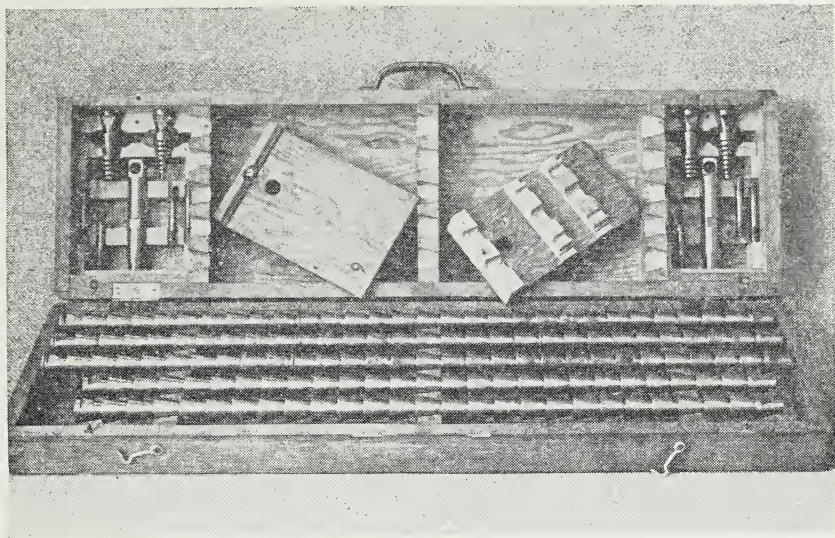


FIGURE 2.—Sectional spud developed by Soil Conservation Service for measuring thickness of sediment.



FIGURE 3.—Survey party taking measurements of sediment thickness. The man in the front of the boat points his thumb to the upper limit of sediment penetration, as measured by samples on the spud.

original storage capacity of the reservoir may be estimated by the use of simple formulas.⁷

Spudding is less successful in lakes that are far advanced in stage of silting, where sediment depths are commonly more than 15 feet, where the sediment has been exposed to prolonged air drying, or where the sediment is predominantly coarse-textured sand or gravel rather than fine silt or clay. In such lakes an estimate of storage loss may be made by soundings from water surface, providing an original contour map of the reservoir basin is available for comparison. Using this practice, measured water depths, corrected to spillway elevation, are subtracted from original depths determined from the contour map to compute the thickness of sediment at points in the lake. These derived thicknesses are then used in the same manner as those measured with the spud. As an alternative new contours representing the top of the sediment may be drawn in an approximate manner from the measured present water depths. By comparison of areas enclosed by old and new contours, the approximate volume of sediment can be calculated by the use of the modified prismoidal formula (45, pp. 162-163).

Reconnaissance surveys of moderate-sized reservoirs up to about 10,000-acre-foot capacity can be made by a specialist in this work in one day with one helper and a motor boat. The results provide a satisfactory basis for estimating the order of magnitude of the remaining useful life of the reservoir, such as 10, 20, 50, or 100 years.

The detailed reservoir survey differs from the reconnaissance survey in that it involves a standardized engineering measurement of the original and present capacities of the reservoir as well as the sediment volume. The survey includes horizontal control by surveying instruments of all measurements (figs. 4 and 5). For reservoirs of more regular shape with few embayments or long winding arms, the maximum error of the detailed survey should be no more than 2 percent of the true capacities. For more irregular reservoirs the error in range surveys may run as high as 5 percent. A complete description of the methods used in making the detailed surveys is contained in a publication of the Department of Agriculture (45, pp. 153-168).

These detailed surveys differ also from reconnaissance surveys in that all survey stations are monumented to permit future repeat surveys on an exactly comparable basis, thus providing checks on the progress of sedimentation at such intervals of time as may be considered desirable. Furthermore, the data permit derivation of relatively accurate indices of sediment production or net erosion from the drainage area. These computed "indices of erosion" in terms of acre-feet per square mile or similar units may be used by extrapolation in estimating the probable rates of sediment delivery from adjacent or similar watersheds.

Detailed surveys require the services of four or five men, and take up to 3 weeks of field work on reservoirs of less than 10,000-acre-foot capacity.

⁷ Instructions for making such surveys are available upon request from the Sedimentation Section, Soil Conservation Service, Washington 25, D. C.

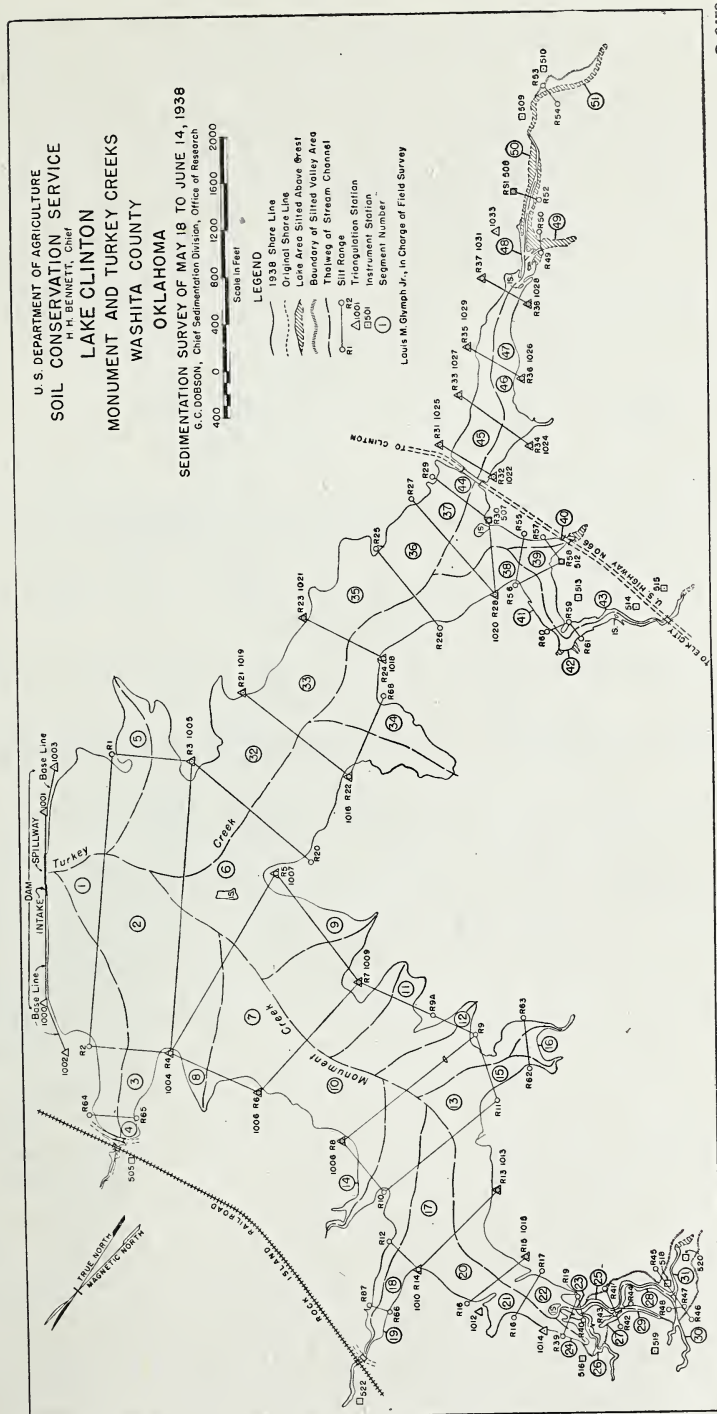
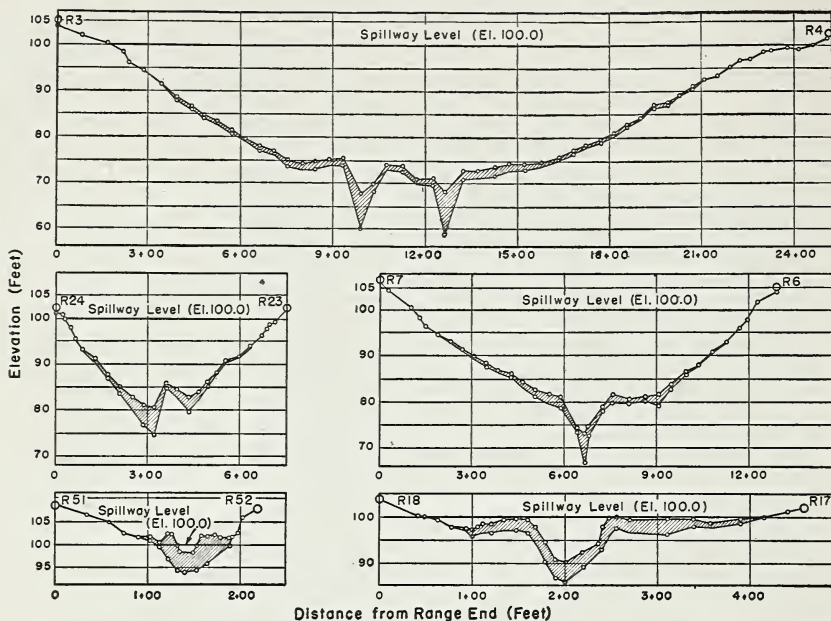


FIGURE 4.—Map of typical reservoir surveyed by the range method, Lake Clinton, Washita County Okla.



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FIGURE 5.—Representative cross sections of ranges on Lake Clinton, Okla., showing sediment deposits.

EFFECTS OF SILTING ON DIFFERENT TYPES OF RESERVOIRS

Reservoirs of equal size but of different uses are not necessarily damaged to a like degree by the same incoming load of sediment.

A power reservoir is damaged by silting only insofar as its full usefulness depends on storage or pondage. The first purpose of all power dams is to create or develop a waterfall so that power can be generated as water descends from near the crest of the dam to the level of the stream below. The primary power available at a waterfall is the power that can be generated continuously from the lowest flow of the stream. Secondary power, which can be developed intermittently when the stream's discharge is in excess of the minimum constant flow, has a much lower value than primary power.

Many power dams are built in steep canyons or on rapids to develop power solely from the unregulated flow of the stream. Other power dams are built at sites where water can be impounded in reservoir basins during periods of high stream flow for release during periods of low flow. This practice leads to a greater constant discharge at the dam and increases the rate of primary-power production. In this type of power reservoir any degree of silting above the lowest level of draw-down causes some damage, inasmuch as the capacity of the reservoir for storage of high water flows is diminished and, therefore, the minimum constant flow that can be maintained decreases. This loss progresses until a point is reached at which the storage space behind the dam is no greater than the space occupied by the original stream channel within the original reservoir

area. With all storage capacity gone, the power plant then has no greater resources to draw on, so far as that reservoir is concerned, than the available natural stream flow.

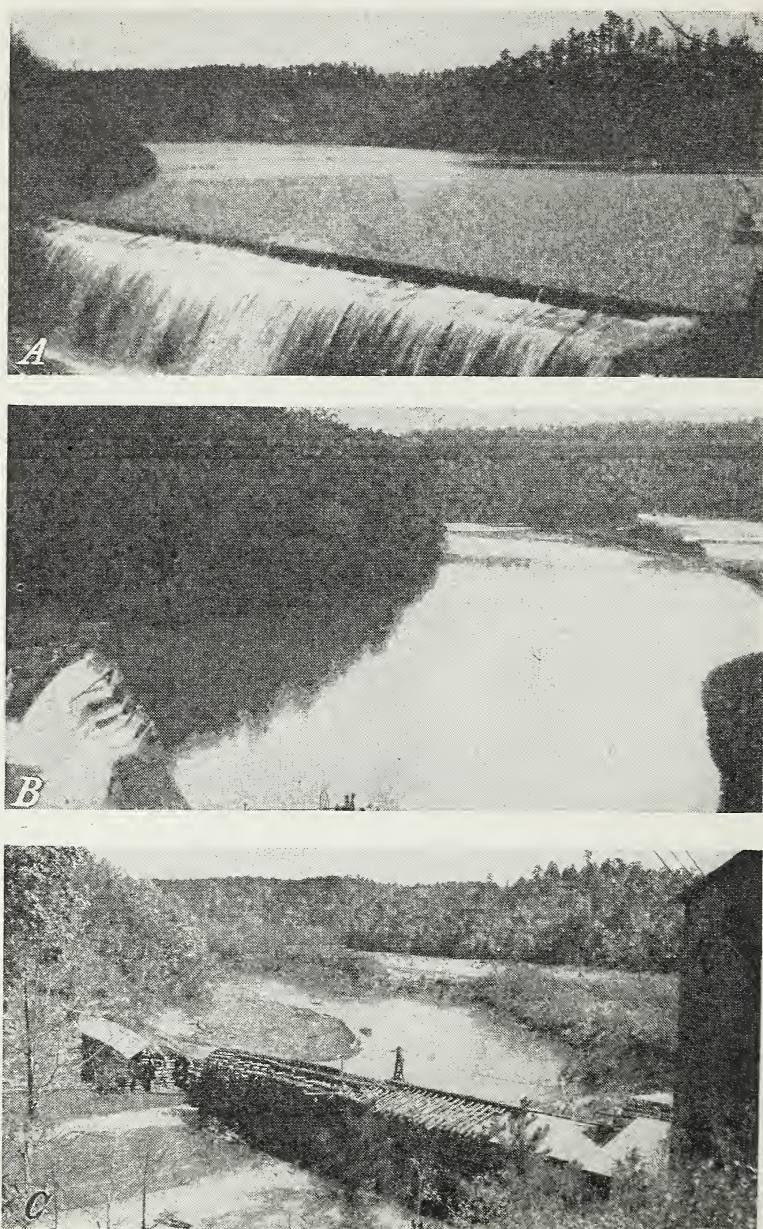
- In practice, power plants are seldom designed to develop power from the entire flow of a stream, for a reservoir of the size required to impound the total flow during years of high discharge would be uneconomic except in some multiple-purpose reservoirs. Even the larger power reservoirs are of such a size, in relation to the flow of the streams on which they are located, that during one or more periods of most years water in excess of that which can be stored is lost over the spillway.

If periods of spillway overflow are followed by periods of low runoff during which the stored water is drawn off to the lowest possible level, the direct loss from silting may be measured by the kilowatt hours of electrical energy that could have been produced by previously lost water equal in volume to the sediment in the useful storage area of the lake and distributed at elevations proportional to elevations of the deposits. Direct physical loss of services by silting occurs only in the years when storage must be called on to its full limit to supplement the deficiency of stream flow.

Over a long-term period, however, the damage is more than that represented by the total losses in kilowatt-hours during periods of low stream flow, for the continuity in the rate of generation of electricity makes the difference between primary and secondary power. The true loss is measured by the difference in sale value between (1) a constant flow of primary power at a higher rate of production and (2) a constant flow at a lower rate, plus the value of secondary power produced in periods of greater flow. This difference or loss becomes progressively greater, because the primary power rate declines theoretically in direct proportion to reduction of storage.

Silting damages not only the large power reservoirs but also the smaller reservoirs that contain only channel storage, or pondage. Many such reservoirs throughout the country develop power for local mills and other enterprises that operate normally only during daylight hours. These reservoirs, when constructed, would ordinarily store sufficient water in the channel above the dam at night to boost power rates during operating hours of the day, or to meet other fluctuations in load or water supply. The silting of channel reservoirs, such as those on Deep River in North Carolina, has caused considerable damage in that the power output is no longer boosted by overnight pondage during periods of low flow (105). Figure 6 shows a typical reservoir of this class in three stages of its history.

Sediment causes other damages to hydroelectric power developments which do not enter into the problem under discussion here. Abrasion of turbines, for example, is generally much less when water passes through a large impounding reservoir than in run-of-the-river plants or in reservoirs almost filled with sediment. In power reservoirs there is nearly always a dead-water storage level, or a level in the lake below which water cannot be withdrawn for power purposes. Silting below this level causes no damage. The cost of some dams has been increased, however, by extra reinforcements to compensate for anticipated pressure of sediment against the dam.

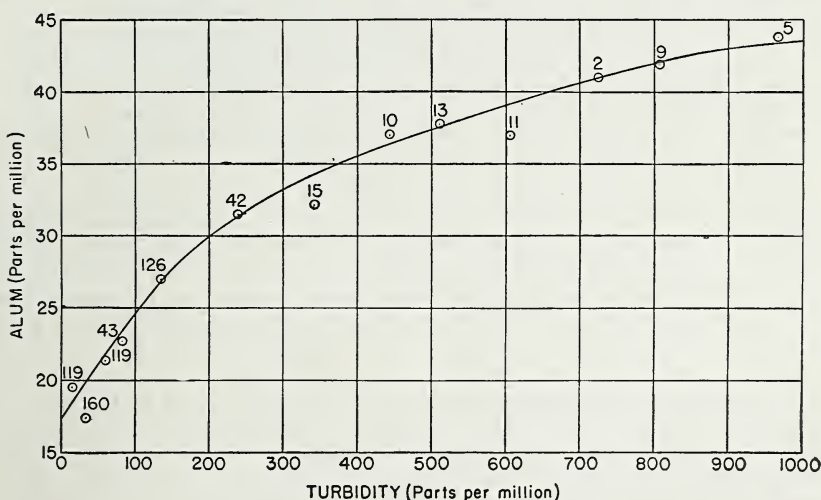


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FIGURE 6—Life history of a typical smaller power reservoir in the southern Piedmont—Dunlap Reservoir on the Chattahoochee River near Gainesville, Ga., built in 1904 with an original capacity of more than 6,000 acre-feet. A, View in 1914. B, View in 1934, when islands of sediment extending nearly to the dam were clearly visible. C, View in 1937, after the reservoir was completely filled with sediment. The dam washed out in October 1936, and the original stream channel is nearly reestablished. The sediment flat in the background was used as a cornfield in 1937 at the time of this photograph.

Damage to water-supply reservoirs is represented by any reduction of the storage capacity below the minimum required to safeguard the continuity of a supply fully adequate for present or estimated future needs. Sufficient capacity must be maintained in water-supply reservoirs to assure continuity of supply during periods of prolonged drought, to meet reasonable expected increases in water demand, and to provide for sudden emergencies, such as those occasioned by major fires. If water-supply reservoirs are built with capacities in excess of these reasonable requirements, then the additional cost of this excess capacity represents, in effect, prepaid insurance against loss by silting. If the capacity is just equal to the reasonable requirements, any reduction in this capacity by silting represents a direct damage, which involves both an accumulating loss of service value and a future replacement cost. The economics of this problem are discussed by Garin and Forster (58).

Another damage by sediment is represented in the cost of filtering a water supply. Although this is distinct from the problem of reservoir silting, it should be recognized that many forms of silting control may be expected to decrease the cost of water treatment. Garin and Forster found that the average cost of water treatment in 22 North Carolina Piedmont cities, including overhead charges and amortization of plants and equipment, is about \$70 per million gallons. For treatment alone, the cost is \$27, of which \$5 is for the cost of chemicals, primarily alum used for flocculation. The relation of the consumption of alum to turbidity is shown in figure 7. Garin and Forster estimated that a 30-percent reduction in the suspended load of the streams, a modest expectation from an adequate erosion-control program, would result in an average saving of \$1.50 per million gallons in the cost of treatment. They concluded that other savings



9565

FIGURE 7.—Graph showing the relation of turbidity to consumption of alum for water filtration. This is a composite curve of 674 individual records from 12 representative filter plants in the Piedmont section of North Carolina. The numbers next to points of the curve represent the number of records averaged in each range of turbidity. (After Garin and Forster.)

resulting from smaller capital outlay for new settling basins and filter plants and from reduced costs of flushing and other plant operations would eventually bring the total savings to \$7 per million gallons, or \$94,500 annually for these 22 cities. Capitalized at 5 percent, the present value of a 30 percent smaller sediment load in water purification alone would be \$1,890,000.

In irrigation reservoirs the damage caused by sedimentation may be measured primarily in terms of the value of water wasted over the spillway that could have been retained except for sedimentation. Where reservoirs, such as Elephant Butte, San Carlos, and Roosevelt, are built with sufficient capacity to impound two or more times the average annual stream flow, water wastage over the spillway may be expected only in years of exceptional flood discharge, and water deficiency may be expected only in exceptional droughts of, let us say, 25-year average recurrence interval. Any deposition of sediment in these reservoirs represents a loss of just that much space for storage of water during the years of high flow, and thus increases the frequency of years of deficient supply. In other words, after a few years of silting a drought of 15-year instead of 25-year average recurrence interval, as initially, may require a reduction in acreage or cause a partial crop loss. This damage may be converted to monetary terms by estimating the value of crops that could have been produced with a volume of water wasted during years of high flow equal to but not exceeding the volume of sediment deposits. The frequency of such damage increases as the capacity is lost, until it becomes economically intolerable, and remedial steps are taken, involving in most instances to date the creation of new storage capacity.

Increased evaporation is another type of damage from reservoir silting in most irrigation reservoirs. Sediment progressively fills the narrower, deeper parts of the reservoir and causes a greater surface area of water to be exposed for any water volume in storage. The less the average depth of water and the greater the surface area exposed per unit of water in storage, the greater is the quantity of water lost by evaporation. In the drier, hotter sections, this increased evaporation loss over a period of years may represent a substantial part of the total loss or damage resulting from sedimentation.

Flood-control reservoirs are designed with a capacity sufficient to hold back a flood of a certain magnitude, which on the basis of probabilities should recur on an average of once in a term of years. The reservoir may be designed to hold back the greatest flood that could occur under the most unfavorable combination of circumstances, but more often it is designed to impound all flow above bank stage of a flood of certain estimated average recurrence interval, as, for instance, a 100-year recurrence interval.

Any degree of sedimentation within the flood-control storage basin obviously means that the dam can impound a smaller amount of water and hence could control to an equal degree only a flood of lesser average recurrence interval than that for which it was designed. If a flood-control dam were determined to be economically justified to control floods of 100-year average recurrence interval, then a reduction of its efficiency by sedimentation to the point where it would control a flood of only 75-year average recurrence interval represents a damage that might be measured on the basis of the computed benefits for the original project.

Numerous flood-control reservoirs are also multiple-purpose reservoirs. The flood-control storage may be the upper 5, 10, or 50 feet of storage above the pool level maintained for power production, water supply, or irrigation. In this type of reservoir the reduction of flood-control storage capacity ordinarily proceeds very slowly and may not be seriously affected until the storage at lower levels is greatly depleted by sedimentation. It should be anticipated, however, that as the large multiple-purpose reservoirs in this country lose capacity, the revenue-producing power or irrigation storage will be maintained by reducing the storage allotment for flood control, unless alternatives such as additional storage or desilting measures are provided.

Reservoirs constructed solely for flood control frequently have outlets in the dam that are uncontrolled by gates. The outlets are of such size that the flow downstream will be slightly below bank stage. The water passes through the reservoir relatively rapidly, and a considerable part of the sediment load is not deposited in the basin. The reservoirs constructed by the Miami Conservancy District in Ohio are examples of this type.

In general, flood-control reservoirs in this country are less subject to sedimentation damage than most other types. Exceptions that may be noted are the relatively small flood-control reservoirs in the mountain canyons adjacent to Los Angeles, and a few flood-control reservoirs located on streams that carry exceptionally large sediment burdens, one of which is the John Martin Reservoir on the Arkansas River near Caddo, Colo.

Recreation reservoirs are damaged, not only by complete filling with sediment, which may result in their ultimate abandonment, but currently because sediment (1) creates conditions unfavorable to fish life; (2) accumulates on sandy beaches, thereby making them less desirable for swimming; and (3) causes swamping at the upper end of the lake and around the shores, thereby decreasing esthetic values and, in some sections of the country, increasing health hazards from malaria.

Navigation reservoirs are damaged both by shoaling of ship channels, necessitating frequent or constant dredging operations, and by loss of storage capacity required for regulating low-water flows.

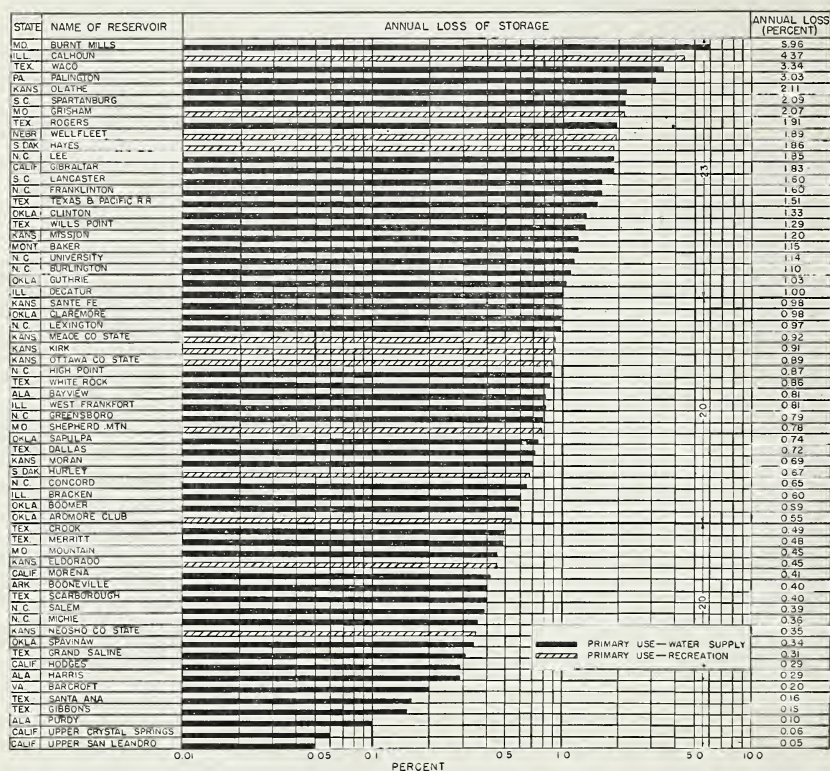
THE MAGNITUDE OF SILTING DAMAGE

The useful capacity of a reservoir is that percentage of a reservoir's total capacity which, when depleted, will essentially terminate the usefulness of the reservoir, barring the development of supplementary storage.⁸ The useful life of a reservoir is the period of years required to deplete its useful capacity.

In an economic study of damage by sedimentation to reservoirs in the Trinity River drainage basin in Texas, Garin and Gabbard (59) found that the useful capacity of 23 reservoirs, most of them built for water supply, ranged from 38 percent to 85 percent of the total original capacity. The average useful capacity of these reservoirs was 60 percent.

⁸ Useful capacity should be distinguished from usable storage, or effective storage. The latter represents all storage above a certain level in the reservoir that can be drawn off for consumptive use, such as for water supply or for power generation. The operation of a reservoir generally becomes uneconomical before the entire usable storage capacity is depleted. Therefore, the useful capacity will be smaller than the usable storage and will be an even smaller part of the total storage.

As a basis on which to analyze the significance of the silting problem in the Nation's water-supply reservoirs the writer (31) has made three assumptions: (1) that the useful capacity of water-supply reservoirs on an average is equal to 80 percent of the total original capacity, which is more conservative than the findings in the Trinity River Basin, Tex.; (2) that decrease of the useful capacity will proceed at a uniform rate until it is exhausted; and (3) that the 151 water-supply reservoirs that comprise the sample represent a fair cross section of conditions over the whole country. Based on these assumptions,



9681

FIGURE 8.—Rates of silting in typical water-supply reservoirs of the United States.

it is estimated that as a result of silting alone 21 percent of the Nation's water-supply reservoirs will have a useful life of less than 50 years, another 25 percent will last 50 to 100 years, whereas only 54 percent will provide enough storage to suffice for present requirements (not the estimated future needs) 100 years hence. Figure 8 gives a diagrammatic illustration of rates of silting of water-supply reservoirs in the United States.

It is probable that irrigation and recreation reservoirs will be depleted at similar, if not somewhat faster, rates. Flood-control reservoirs, except for certain types, as those in Los Angeles County, Calif., will be depleted at much less rapid rates, but will furnish progressively less and less flood protection from the date of their completion. Be-

cause of the dual purpose of power dams for head and storage, evaluation of the effect of silting on power reservoirs is complicated to such an extent that no adequate analysis of the national aspects of silting on this class of reservoirs has yet been possible. The damages are known to be large, however, and may exceed those of any other class.

Studies of the economic aspects of reservoir silting are just beginning, and thus far even estimates of the total annual damage by silting to American reservoirs are of doubtful value. Economists still have widely different points of view on the methods of appraising damages.

In their recent study of 23 reservoirs in the Trinity River Basin, Tex., Garin and Gabbard (59) computed the average annual damage due to sedimentation as \$165,000. The original cost of these 23 reservoirs was approximately \$16,350,000. In a similar study of 22 water-supply reservoirs in the Piedmont section of North Carolina, Garin and Forster (58) computed the annual damage as \$32,000. The original cost of these reservoirs, many of which are small, was \$2,030,000. In a recent study of the new Morris Sheppard Reservoir on the Brazos River in Texas, Garin (57) estimated that the annual damage by, silting would amount to \$67,416. This figure is based on a rate of filling estimated from suspended-load observations during the period 1924 to 1934. The cost of this reservoir, dedicated July 2, 1941, was \$5,800,000.

A study of the effects of silting on the output of power reservoirs in the South Atlantic and Eastern Gulf drainage basins of North Carolina, South Carolina, Georgia, and Alabama during the drought year 1941 revealed a net loss of about 90,000,000 kilowatt-hours as a result of depleted storage capacities. At the cheapest rates for secondary power, this amount of electricity has a value of more than \$250,000.

On the basis of these and a few other economic studies, it seems apparent that the average annual damage to all reservoirs in the United States is not less than \$10,000,000. Damage may be several times this amount, perhaps as high as \$50,000,000 annually.

A discussion of the regional aspects of reservoir silting is beyond the scope of this publication. In reservoirs that have comparable ratios of capacity to average annual inflow or watershed area, rates of silting are closely proportional to rates of erosion in their drainage basins. Bennett (22, pp. 617-867) has given a detailed discussion of conditions of erosion in the various physiographic provinces of the United States, and the reader is referred especially to this publication for information on particular areas. In an earlier publication, Ashe (16, pp. 17-32) discussed the relation between forest cover, soils, and the sediment load of the main stream systems in the United States. The author (33) has given a brief summary of the regional aspects of reservoir silting in water-supply reservoirs.

METHODS OF SILTING CONTROL

All the methods proposed or tried for the control of reservoir silting may be classified into six groups, namely, (1) selection of the reservoir site, (2) design of the reservoir, (3) control of sediment inflow, (4) control of sediment deposition, (5) removal of sediment deposits, and (6) watershed erosion control. These six groups represent three approaches to the problem of control. Groups 1 and 2 are methods of minimizing sedimentation damages by controlling the location and

size of the reservoir. Groups 3, 4, and 5 include various methods of preventing all or part of the sediment from being permanently deposited in the reservoir. The third approach attempts, through control measures in the watershed, to reduce the quantity of sediment that will reach the reservoir.

A sound policy of reservoir-silting control requires impartial consideration of all three approaches and selection from the various methods available of those that may be physically possible and economically feasible under any particular set of conditions. A careful weighing of the advantages and disadvantages of the various methods before the reservoir is definitely located and designed is most likely to lead to the best solution of the problem. When only one site is available, the first possibility for sedimentation control is already eliminated. When the reservoir is designed and built, one or more additional possibilities are forfeited. After sediment has been deposited in the reservoir, there are then only a few possibilities left. In this field as in most others involving engineering economics, proper planning at the earliest stage will lead to the greatest return.

SELECTION OF THE RESERVOIR SITE

Whenever a water-storage project permits a choice of sites for the dam and reservoir basin, careful study should be given to the quantity and type of sediment load that will be produced by the respective drainage basins above the alternate sites. Both the total quantity and average size distribution of the load are governed by such characteristics of the drainage basin as soil types, slopes, stream gradients, land use, and the extent of erosion of land slopes and stream channels. Often significant, but not obvious, differences may be found in adjacent drainage basins by appropriate surveys.

In India (114, pp. 56-57), Switzerland (99), and elsewhere, it has been clearly recognized that the rate of silting is one of the critical factors to be considered in choosing between alternate sites. This factor should be given more attention in America.

In estimating the sediment production of a drainage area, three types of data should be considered: (1) Results of reservoir sedimentation surveys, (2) records of the suspended load of streams, supplemented by new methods of estimating bed load, and (3) conservation surveys.

The results of numerous reservoir surveys have been summarized in publications of the Soil Conservation Service.⁹ Most of the surveyed reservoirs trap from 70 percent to nearly 100 percent of the sediment delivered to them by inflowing streams. The records of accumulation in reservoirs more than 10 years old are, therefore, useful indices of the average annual rates of sediment production from many types of drainage areas.

Nearly 1,000 suspended-load records¹⁰ on American streams are now in existence. Most of the older data were summarized by Stevens (113). Since the appearance of his paper extensive programs

⁹ The Sedimentation Section, Soil Conservation Service, Washington 25, D. C., will furnish on request, a list of publications on reservoir-silting surveys.

¹⁰ A record, as used here, means the results of systematic stream sampling during a given period of time from which the tonnage of suspended load passing the sampling station during that period can be calculated. There may be several records for the same sampling station on a stream, separated by months or years during which no samples were taken.

of stream sampling have been conducted by the United States Army Engineers, U. S. Geological Survey, Soil Conservation Service, Tennessee Valley Authority, and several other agencies. Much of these data remains unpublished. Records of the locations of sampling stations and the periods of measurement, although not the results, are maintained by the Sedimentation Section of the Soil Conservation Service. Most of these data could be obtained and should be utilized, so far as they are applicable, in estimating sediment production from drainage areas.

A series of comprehensive reports on sediment-load samplers, technique of sampling, and methods of analysis has been prepared at Iowa Institute of Hydraulic Research (119) on the results of an investigation sponsored by several Federal agencies. New methods have been developed by the Soil Conservation Service for the measurement of bed load transported by small streams.

Conservation surveys made by the Soil Conservation Service for farm-planning operations include measurements of the degree of accelerated erosion of the land surface (94). At present the results of these surveys cannot be used satisfactorily to make quantitative estimates of the amount of sediment transported out of the mapped drainage areas, but they are extremely valuable in comparing the relative extent and seriousness of erosion in drainage areas above the alternate reservoir sites. Inquiry regarding the existence of completed surveys for any particular drainage area or the possibilities of having surveys made in any area may be addressed to the State Conservationist of the Soil Conservation Service in any State.

Estimation of the sediment load that will reach any proposed reservoir site requires either (1) extrapolation from reservoir-sedimentation or suspended-load data obtained at other sites in the same or similar drainage basins, or (2) the measurement of the stream load during a period of years at the proposed site. In general, unless measurements can be continued for at least 5 to 10 years, reservoir silting records offer the most satisfactory basis of estimation, but they should be checked by suspended-load records and conservation-survey data wherever possible.

Appraisal.—The possibility of choosing alternate reservoir sites for water storage is largely confined to smaller reservoirs but is particularly applicable to water-supply, stream-regulating, and recreation reservoirs.

Power dams must be located where the needed head for power generation can be obtained, and storage capacity often must be subordinated to this requirement. Two factors, other than a safe dam site and adequate stream flow, primarily govern the design of a power project. One is the distance from sources of power consumption. A few decades ago when power transmission over long distances was technologically unfeasible, this was a primary factor. It is gradually becoming less and less so, although even today power sites several hundred miles distant from points of consumption may compare unfavorably with alternate sources of power, such as steam-generated electricity. The second factor is that the greatest head should be developed for any given flow at the least cost per unit of installed generating capacity. Furthermore, power sites are being developed so rapidly that in a few decades virtually all the more favorable ones will have been utilized. Even today there is seldom an opportunity for choice

between two sites based on the effect of the silting problem. These considerations do not apply, however, to stream-regulating or head-water-storage reservoirs constructed to develop more constant flow at downstream power dams.

Irrigation reservoirs must be located where the water is. Like power dams, irrigation dams are being constructed so rapidly that in a generation or two storage capacity will be developed for all the available runoff in the Western States, excepting occasional years of very high stream flow. Today in some places there are possibilities of deferring the silting problem on smaller irrigation projects by building an impounding reservoir at higher altitudes where vegetal cover is more complete and erosion less extensive or off channel. (See pp. 51-58.) Or there still may be some choice between drainage basins on one of which the range has deteriorated less from overgrazing and erosion has not progressed so far as in an adjacent area.

Navigation reservoirs are obviously restricted to a particular site on a particular stream if their purpose is to provide a pool for the transit of boats. If their purpose is solely to provide storage for regulating stream flow, they may occasionally be constructed at higher altitudes or in rougher country where better forest cover prevails.

In selecting sites for water-supply and recreational reservoirs, especially where they are smaller developments ranging from a few hundred to a few thousand acre-feet in capacity, serving smaller cities, towns, and local communities, a choice of drainage areas still exists in most parts of the country. In the eastern half of the United States the supply of sites for these smaller reservoirs will last for many generations. In the more arid regions their number is naturally more limited, but at least as far west as the Great Plains there is still a choice of drainage areas. Engineering studies, of course, will show that the cost of developing an impounding reservoir at one site is less than at any other site for the particular service desired. If, however, a reliable estimate is made of the prospective rate of reduction of the useful life of the reservoir by silting, it may be found that the construction of a lake at an alternate site, even though initially more costly will be ultimately cheaper.

Not only should the present sediment production from the alternate drainage areas be considered, but also the possibilities of utilizing other methods of silting control should be taken into account, especially watershed erosion control through land purchase and reforestation, and through soil conservation districts. Landownership and values in the two drainage basins are important factors to be investigated. The response of the landowners to cooperation in erosion-control programs and their willingness to sell land at reasonable prices are matters of importance.

DESIGN OF THE RESERVOIR

Two elements affecting the rate of silting should be considered, especially in designing an impounding reservoir. One is the total capacity to be provided, and the other is the design of water and sediment release works in the dam.

The capacity of an impounding reservoir is ordinarily governed by a number of factors, among which are (1) the physical characteristics of the dam site and impounding area, (2) the estimated available

runoff, both total and during periods of low flow, (3) the service requirements of the reservoir, and (4) the funds available for its construction. Other factors must be considered in certain types of reservoirs, as those for power, where head usually must be given primary weight. The factor of potential loss of storage by silting has been considered to the extent of influencing design in only a few existing reservoirs in this country, these being principally in large irrigation reservoirs of the Southwest.

DEVELOPMENT OF A SUITABLE CAPACITY-WATERSHED RATIO

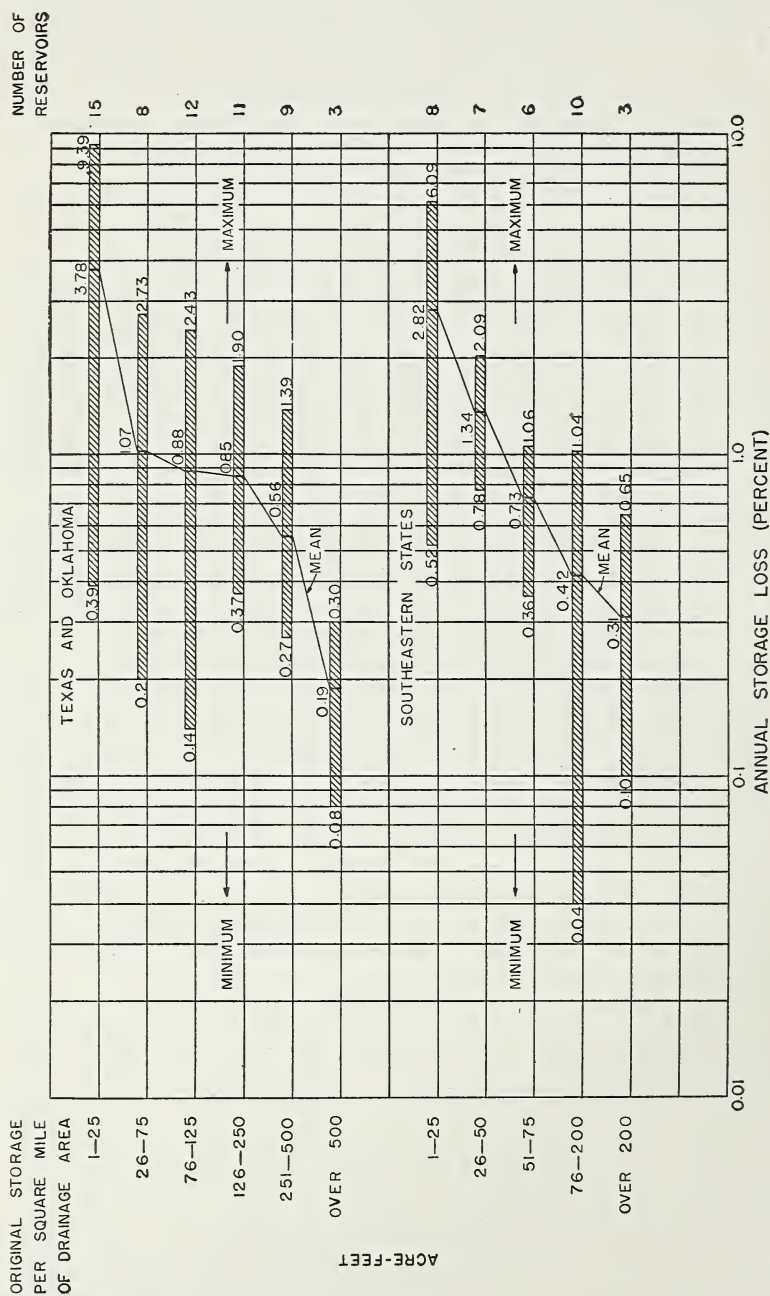
Study of reservoir silting, both in this country and abroad, has shown that one of the most important factors governing the rate of storage loss is the ratio between the original storage capacity of the reservoir and the inflow of water from the drainage basin. In this country the general lack of stream-flow records from smaller drainage areas, especially from those of less than 100 square miles, has made it difficult to use capacity-inflow ratios in engineering investigations. In any region of relatively uniform climate, topography, and soils, however, a ratio of storage capacity to watershed area may be used satisfactorily, inasmuch as the average runoff per square mile will not vary greatly.

All of the reasonably reliable data on annual rates of storage loss in the Texas-Oklahoma region and the Southeastern States region have been separated into groups depending upon the original storage of the reservoir per square mile of drainage area. The data were then plotted to show the minimum, mean, and maximum rates of annual storage loss in each group of reservoirs (fig. 9).

Clearly, reservoirs in either region that have an original capacity of less than 25 acre-feet per square mile of drainage area are likely to have an exceptionally high rate of silting. Lake Austin, on the Colorado River at Austin, Tex., has been the classical American example of reservoirs in this category (116). Old Lake Austin, completed in May 1893, and destroyed by a flood in April 1900, had an original capacity of 49,300 acre-feet, or 1.30 acre-feet per square mile of drainage area. Its capacity was depleted at a rate of 7.1 percent annually during these 7 years. New Lake Austin, completed in the summer of 1913 with an original capacity of 32,029 acre-feet, or 0.84 acre-foot per square mile, lost its capacity at the rate of 7.34 percent annually from that date to August 1926.

More recent examples are not difficult to find. In 1936 a water-supply reservoir was built at a cost of about \$150,000 on the Solomon River at Osborne, Kans. The reservoir capacity was small, only about 300 acre-feet, but presumably adequate to supply the needs of Osborne. The drainage area, however, was about 2,100 square miles, so that the storage capacity was only 0.14 acre-foot per square mile. The reservoir was completely filled with sediment the first year after its completion. Records of at least a dozen similar failures of reservoirs constructed since 1930 are available.

A comparison of the silting rates of Lake Waco on the Bosque River at Waco, Tex., and of Bridgeport Reservoir on the West Fork of the Trinity River above Fort Worth, Tex., affords an excellent illustration of the effect of the capacity-watershed ratio. Both of these lakes were created primarily for water supply. Lake Waco



C-9933

FIGURE 9.—Relation of storage capacity-watershed area ratio to the annual rate of silting in reservoirs of the Texas-Oklahoma region and the Southeastern States.

had an original capacity of 39,378 acre-feet and a drainage area of 1,662 square miles. The capacity-watershed ratio was, therefore, 24 acre-feet per square mile. Lake Bridgeport, with an original capacity of 292,000 acre-feet (exclusive of flood storage) and a drainage area of 1,051 square miles, had a capacity-watershed ratio of 278 acre-feet per square mile. Sedimentation surveys of the two reservoirs showed that the rates of sediment production from the two drainage areas were remarkably close, Lake Waco accumulating sediment at the rate of 0.80 acre-foot per square mile annually, and Bridgeport Reservoir 0.77 acre-foot per square mile annually. Because of the difference in ratio of storage capacity to drainage area, however, Lake Waco lost 3.34 percent of its capacity annually (1930-36), whereas Bridgeport Reservoir lost only 0.27 percent of its capacity annually (1932-43).

Figure 9 suggests that in the Texas-Oklahoma region careful consideration should be given to the silting factor in any reservoir projected with a capacity of less than 250 acre-feet per square mile of drainage area. There are large parts of these States, of course, in which rates of sediment production from drainage areas will not exceed 0.5 to 1.0 acre-foot per square mile annually, and, at such rates, reservoirs with ratios of 100 acre-feet of storage per square mile of drainage area, or even less, should have a useful life in the order of 75 or 100 years. Some areas, such as the Blacklands, however, have rates of sediment production as high as 5 acre-feet per square mile, or more, annually, and thus require capacity-watershed ratios of more than 250 acre-feet per square mile to have reasonably long lives under existing watershed conditions.

In the Southeastern States it is apparent that original storage capacities of more than 75 acre-feet per square mile should be obtained, on an average, in order to keep the expected rate of silting reasonably low. Under average conditions of land use in the southern Piedmont, a sediment production of 0.5 to 0.75 acre-foot per square mile annually may be expected. Less than 40 percent of land in cultivation tends to reduce the rate below this range, whereas more than 60 percent in cultivation, unusually steep slopes, or extensive urban areas, tend to increase the rate.

A number of well-known reservoirs were designed with a capacity in excess of storage requirements to provide for loss by silting over a period of years. Lake Mead, impounded by Boulder Dam on the Colorado River, has 5,000,000 to 8,000,000 acre-feet allotted for storage of sediment out of a total capacity of 32,359,274 acre-feet. Elephant Butte Reservoir, on the Rio Grande, was designed with a capacity of 2,638,860 acre-feet, although the maximum storage required to meet anticipated irrigation needs and to hold over seasonal runoff in most years was less than one-half of this amount. San Carlos Reservoir on the Gila River was built with a capacity of 1,247,999 acre-feet, although the long-term mean annual flow of the Gila is only about 400,000 acre-feet.

According to Orth (95), the Qued-Fodda Dam in Algeria was designed with a surplus capacity of 24,300 acre-feet to provide for silting over a period of 60 years, and the new Puentes Dam in Spain with an additional 2,430 acre-feet to provide for silting during 20 years. Sutherland (115) states that the Sautet Dam, built for hydroelectric

power on the Drac River, a headwater tributary of the Rhone in France, has the lower 24,000 acre-feet out of a total capacity of 106,000 acre-feet reserved to provide for storage loss. It has been estimated that at the prevailing rate of deposition this will suffice for 100 years. The largest irrigation reservoir in India (1932), created by the Nizam-sagar Dam on the River Manjra, contains 94,123 acre-feet for sediment storage out of a total capacity of 681,813 acre-feet, excluding flood storage (10).

Appraisal.—When the service requirements of a new reservoir call for a storage capacity so large that the capacity-watershed ratio is several hundred acre-feet per square mile, no apprehension need be felt over premature exhaustion of the reservoir capacity by silting. For example, the multiple-purpose Norris Reservoir, built a few years ago by the Tennessee Valley Authority on the Clinch River, Tenn., with a capacity of 2,567,000 acre-feet, can store 870 acre-feet of water for each of its 2,950 square miles of drainage area. If, in consideration of the fact that many parts of the watershed have suffered severe erosion, a silting rate as high as 1 acre-foot per square mile were assumed, the storage capacity would be less than half depleted in 400 years.

Most of the reservoirs in the Muskingum Watershed Conservancy District, Ohio, the Sardis Reservoir on the Tallahatchie River, Miss., the Wappapello Reservoir on the St. Francis River, Mo., and other similar large flood-control projects will not be excessively depleted by silting for a hundred years.

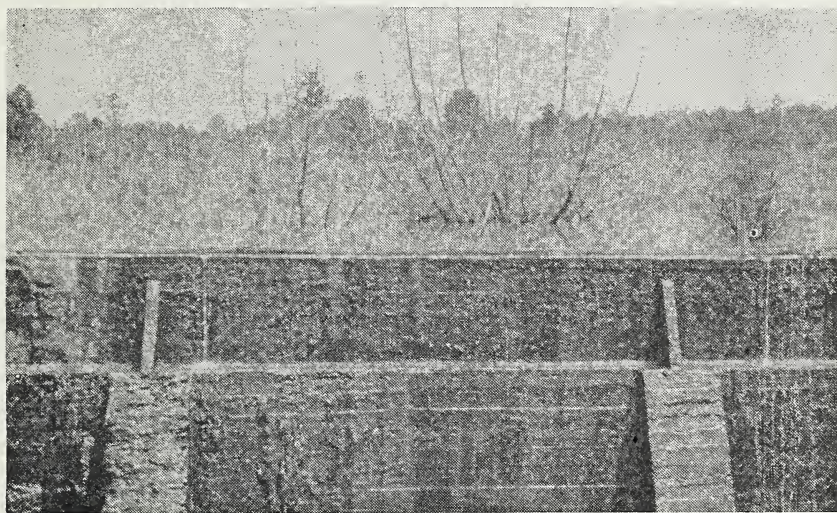
If, on the other hand, smaller reservoirs, similar to the thousands already built for water supply, recreation, irrigation, and even power, are being planned, and it is found that the ratio of storage to drainage area falls in the critical range as indicated by figure 9—that is, if the possible storage loss is in excess of one-half of 1 percent annually—the engineering investigation for the project should include a thorough consideration of the silting problem and methods of silting control.

Once a reliable estimate is made of the rate of silting in a proposed reservoir, as provisionally designed on the basis of service requirements and probable runoff, the question of increasing its size, if physically possible, to provide a longer useful life is one of economics. Under any system of economics the minimum life must be one that will assure continued functioning of the project until it is amortized. The period of amortization of most reservoir projects in this country ranges from 20 to 50 years.

From the standpoint of reasonable conservation of reservoir sites, it would seem desirable and prudent to adopt 100 years as the very minimum useful life for which any storage development should be planned.

O'Brien, discussing Stevens' "The Silt Problem" (113, p. 265), pointed out that if a given reservoir continues to need the effective storage capacity originally provided for it, the monetary damage caused by silting should not be computed from the cost of the original reservoir but from the cost of the necessary additional or replacement storage. As the sites where storage can be developed most economically are utilized first, silting of replacement reservoirs of equal capacity causes greater damage, and ultimately it may be impossible to provide sufficient storage capacity at any cost.

Evaporation may be a limiting factor in increasing the size of irrigation reservoirs in the arid States. Tyler, discussing a paper by Taylor (*116, p. 1717*), commented on the problem of providing a capacity that will give a reasonably long life without creating a large surface area from which excessive evaporation losses occur. This difficulty is more acute, he pointed out, where the valleys are shallow and the reservoir volume is distributed horizontally rather than vertically. In such reservoirs considerable shoal water may add very little to the available storage but may allow 50 to 70 inches of water loss annually in evaporation. He concluded that large capacity "is not necessarily a solution for the silt problem, as it introduces another problem quite as troublesome."



3916

FIGURE 10.—Barrett Dam on East Sandy Creek, near Athens, Ga. This small power reservoir was filled with sediment, the dam was raised, and the reservoir is now completely filled with sediment again, except for the stream channel through the original lake area. The power plant has now been dismantled.

RAISING THE DAM

Raising the dam of an existing reservoir, or constructing a new dam so that it can be raised subsequently, may be thought of as simply a deferred adjustment of capacity to watershed area. In most cases of record, dams have been raised to impound additional water to meet increased service requirements; only a few dams are known to have been raised to offset silting losses (fig. 10).

While the project was still in the planning stage, successive raising of the dam of Elephant Butte Reservoir on the Rio Grande, N. Mex., was one of the schemes proposed (*102, p. 880*) to prolong its life. Hill is reported to have considered that the useful service of the reservoir could be extended for 300 years, and although this would not make the reservoir permanent, the plan would make it feasible financially to meet the expense of later storages higher upstream.

Actually, the completion in 1938 of the Caballo Dam, about 25 miles below Elephant Butte, has postponed any need for raising Elephant Butte Dam for many years. Caballo Reservoir, which provides approximately 350,000 acre-feet of additional storage capacity farther down the river, permitted the installation of a power plant and release of water for power generation at Elephant Butte Dam without loss of the water for irrigation.

In connection with the plans for constructing San Carlos Reservoir on the Gila River, the question of raising the dam at a later date versus initial construction to a higher elevation was considered by a special Board of Engineer Officers, U. S. Army (123, p. 33). Based on an estimated silting rate of 3,750 acre-feet annually (subsequently found to be underestimated), the Board concluded that, with 500,000 acre-feet of water storage required, a reservoir with a minimum capacity of 575,000 acre-feet and a dam 168 feet high would be needed to allow for 20 years' accumulation of sediment, this period being the time required for amortization of the project. A dam 180 feet high would allow for sediment accumulation for 55 years, and with additional spillway gates raising the level 5 feet, for 74 years. The difference in first cost of dams 168 and 180 feet high was estimated to be \$210,000.

The Board concluded that increasing the reservoir capacity by raising the dam at a later date "is the cheapest and easiest way of handling, or, as Mr. Davis has aptly said, of evading the silt problem." The Board considered that building the dam to a greater height initially than was necessary to provide the required storage for a longer period than 50 to 75 years was objectionable because it would be taxing the present generation, and perhaps the next, in order to permit later generations to escape the cost of desilting. The Board admitted that future generations might receive value from the project, but considered it inadvisable to defer amortization beyond the present generation; therefore, the Board reasoned that the cost of silting control, which would benefit only future generations, should not be saddled on the present water users.

In an appendix to the Board's report (123, p. 147) Hughes noted logical engineering objections to deferred raising of the dam as follows: (1) Considering the short period of 24 years until the lower dam would need to be raised and the fact that the construction plant would be available and a labor force organized and experienced, the dam could probably be built to full height, 180 feet, initially, at an extra cost of only two-thirds of what the addition would cost at the later date; (2) if the dam was not of the overfall type, the cost of the rock excavations for spillways for the lower dam, part of which would be useless for the higher dam, and the subsequent cost of closing them off to the higher grade would amount to as much as the cost of the upper 10 feet of the final dam; and (3) flooding rights to the higher reservoir level could be as easily and nearly as cheaply acquired initially as the lower one, whereas to raise the line at a later date would doubtless require removal of roads, habitations, and other improvements in the meantime established close to the low-level reservoir.

Appraisal.—Engineering-economic analysis of some reservoir projects probably would show that it is cheaper to build a substantial

lower dam now, and at intervals to raise it until its ultimate height will have given an original capacity in such adjustment to sediment inflow that a long useful life results. Where evaporation is a critical factor, as noted by Tyler, it might be more desirable to maintain a lesser storage capacity by periodically raising the dam than to develop a large excess capacity initially. The arguments advanced by the Army Board and Hughes, as summarized in this section, are logical ones to consider for any new dam. It seems probable, however, that in most cases the more desirable alternative would be to develop the ultimate capacity initially.

The type of construction of existing dams determines whether they can be raised. If additional capacity is required to offset the loss resulting from silting and the strength of the dam and its foundation permit a raise, the cost involved should be compared with the cost of building a supplementary reservoir elsewhere, and of removing part of the sediment now in the reservoir by methods described in succeeding sections.

Several types of existing dams cannot be raised satisfactorily. One of these is the multiple-dome dam, of which the San Carlos Reservoir Dam, as finally constructed to a height of 215.5 feet above the river bed, is a good example. Earth-fill dams with low side slopes require almost as much material to effect a significant raise in elevation as was required for the original dam.

The economic study of proposed reservoirs should compare the cost of building a dam of such a type and strength that it can be raised at a later date with the cost of building dams of other types to impound the ultimate capacity today and with the cost of other methods of sediment control.

INSTALLATION OF ADEQUATE OUTLET WORKS

Outlet works are any controls by which water is released from a reservoir. Outlet works may consist of gates on a permanent spillway, pipes or conduits running through the dam controlled by gates or valves, undersluices controlled by gates, or curtains in front of the dam. The potentialities of the various methods for passing sediment through or over a dam should be considered in the dam design whenever reservoir silting is likely to be a problem.

Spillway gates may be designed to pass maximum flood flows, or they may be smaller and supplemented by emergency spillways at higher elevations. Service outlets in most dams are designed to release no more than 1 or 2 percent of the reservoir's maximum storage in 1 day. Somewhat greater discharge capacity, probably better achieved by more rather than larger outlets, may be required to vent density currents (see pp. 64-74). Much larger outlets are needed for undersluicing (see pp. 74-83). Their total discharge capacity generally should be in the range of from one-third to all of the maximum daily inflow.

The results of density-current investigations by the Soil Conservation Service led the Washington Suburban Sanitary Commission, Hyattsville, Md., to install five 24-inch outlet pipes for venting these currents in its new Ambursen-type dam, constructed on the Patuxent River near Brighton, Md., in 1942. The reservoir will have a capacity

of 20,255 acre-feet when the Tainter gates are installed. Three of the outlet pipes are located over the old channel just above stream-bed level, and two are at higher elevations. Duplicate gate valves just behind the face of the dam control discharge through the pipes. There are also two 20-inch service outlets which will be connected to a power turbine, and which are alone sufficient to release all the flow required for water supply at the intake station downstream. The special outlets are used to prevent spillway discharge insofar as possible. Their discharge capacity at maximum head is about 10 times the mean daily inflow into the reservoir, and about one-fifth of the maximum daily discharge recorded on the Patuxent River in 40 years. Turbidity records obtained from the pipe discharge and from the lake surface indicate substantially higher turbidities from the pipes most of the year and especially after rain in the watershed.

Appraisal.—It is generally costly to reconstruct the outlets of existing dams to provide for more efficient sediment sluicing and prevent clogging of outlets by sediment; but this has been done in various places, as, for example, at dams of the Los Angeles County Flood Control District. In the construction of new dams, however, the possibilities of sediment removal by various methods described in pages 65–114 should be carefully considered in designing the outlet works.

Occasionally a mere change in the location and design of outlets, involving little excess cost, would provide for more effective venting of sediment. Generally, however, some thousands of dollars added cost will be involved in constructing outlet works specially designed to provide for effective removal of sediment, either before it has settled, or by sluicing it or passing it through with heavy discharge. Here again the question involved is a comparison of the cost today of such works as against the benefits to be derived at the end of some period of years.

CONTROL OF SEDIMENT INFLOW

Four principal methods have been used to control the inflow of sediment to impounding reservoirs. These are (1) the construction of settling basins, (2) the propagation of vegetative screens, (3) the location of the reservoir off the main channel, and (4) the construction of bypassing channels or conduits. Such devices are generally thought of as being directly associated with, and adjacent to, the reservoir to be protected. No exact line of distinction exists, however, between settling basins or vegetative screens near the reservoir, installed for the specific purpose of holding back part of the sediment load, and similar structures or practices established throughout the drainage basin for the dual purpose of controlling accelerated erosion and inducing the deposition of erosional debris produced at higher elevations in the watershed.

SETTLING BASINS

Settling basins (sedimentation basins, debris basins) may be formed by building dams or dikes across stream channels, across channels and flood plains, or solely on flood plains if adjacent to channel diversion dams. Settling basins are usually placed at, or a short distance above, the head of backwater of a reservoir. The fundamental

principle of the settling basin is to check the velocity of stream flow and thereby cause the deposition of the stream's sediment load. A small reduction in velocity is usually sufficient to induce deposition of all coarse material, such as sand, gravel, and boulders. On the other hand, settlement of the finer silt and clay, which generally constitutes the major part of the stream load, may require the development of a true stilling pool where water is impounded for hours or days. Most material of silt size will settle out, however, if the flow passes in a relatively thin sheet at low velocity over broad flats, especially if these are densely vegetated.

Settling basins are a very ancient device used to remove sediment from water. Their principles were well known to the Romans who were troubled with sediment in several of the water supplies brought through aqueducts from distant springs and streams. Frontinus in his treatise on "The Water Supply of the City of Rome" during the reign of the Caesars (56, p. 19) says:

The intake of New Anio is on the Sublacensian Way, at the forty-second mile-stone, in the Simbrinium, and from the river; which flows muddy and discolored even without the effect of rainstorms, because it has rich and cultivated lands adjoining, and, as a result, loose banks; for this reason a settling reservoir was built upstream from the intake, so that in it and between the river and the conduit the water might come to rest and clarify itself. But in spite of this construction the water reaches the city in a discolored condition, whenever there are heavy rains. The Herculanean Brook, which has its source on the same Way, at the thirty-eighth mile-stone, opposite the springs of Claudia and beyond the river and the highway, joins it, being of itself exceedingly clear, but losing the charm of its purity by admixture.

Debris-basin dams are usually constructed in the most economical manner from materials at hand, such as earth, rock, and timber. As permanent water storage is not a consideration, the dam need not be impervious. Occasionally, however, where stream gradients are steep, and the sediment load includes large quantities of gravel and boulders, nothing less substantial than reinforced concrete will withstand the tremendous impact of the debris-laden water.

Settling basins through which the main stream flows must have spillway capacities adequate to pass at least ordinary floods. Spillways are generally of the overflow type, and may be constructed either over the original stream channel or on the valley sides, depending on topographic conditions (fig. 11).

As the primary object of a settling basin is to store the largest amount of sediment at the least possible cost, not only should the dam be constructed in the cheapest manner compatible with safety, but also the land subject to deposition behind the dam should be of minimum value. Ashe (16, p. 15) proposed for the Southern Appalachian region that rough alluvial lands, which had been injured by gullying or by deposition of sand and gravel during floods should be utilized for sedimentation basins to protect the large power reservoirs until reforestation programs could be effected. Such lands could be flooded by means of low and inexpensive channel dams, he claims, and although the deposits would reach the top of the dam, except in the stream channel, in a few years the dams will have performed their function as desirable though temporary expedients.

Most settling basins, because their capacity is small with relation to inflow, trap only the coarser parts of the stream load. During the period of their effectiveness they may hold back 10 to 50 percent or

more of the total sediment reaching them. A few basins, however, are relatively large, as those in the Zuni watershed in New Mexico (fig. 11) and the Bennett Basin in Washington (fig. 12). In these basins a high percentage of even the finest sediment has been permanently deposited.



C-8430

FIGURE 11.—Lower Nutria water-storage and sediment-detention basin in the Zuni Reservoir watershed, N. Mex. Note the substantial spillway to the left of the dam.



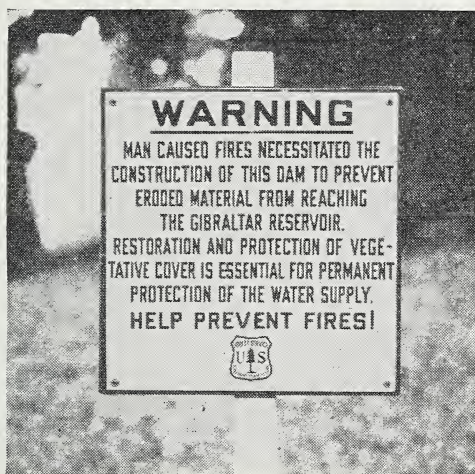
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FIGURE 12.—Bennett Desilting Basin near Wilsoncreek, Wash.

Although settling basins, in general, must be considered temporary expedients, in places provision has been made to excavate the deposits where resulting costs were justified by the benefits of continued protection, or where costs could be defrayed by sale of the excavated sand and gravel. If excavation is feasible, the effectiveness of the settling basin may, of course, be prolonged indefinitely.

The most substantial and permanent type of settling basin is represented by those constructed above Gibraltar Reservoir near Santa Barbara, Calif.

In 1932 and 1933, forest fires swept over 37 percent of the 216 square miles of steep, chaparral-covered slopes of the upper Santa Inez River watershed above Gibraltar Reservoir, which impounds the water supply for nearby Santa Barbara, Calif. This reservoir had a capacity of 14,500 acre-feet when built in 1920. A sedimentation survey made in 1934 revealed that sediment had accumulated since 1931 at an annual rate of 237 cubic feet per acre of drainage area. (See p. 120.) This exceptionally high rate clearly indicated the need for immediate action to keep large additional amounts of erosional debris, derived from fire-denuded slopes, out of the reservoir. In recognition of this situation, the United States Forest Service



6250

FIGURE 13.—Sign erected at Mono Debris Dam in the Gibraltar Reservoir watershed near Santa Barbara, Calif.

constructed two debris dams on tributaries that were yielding particularly heavy sediment loads, in order to retard the movement of sediment until the vegetal cover was regenerated (fig. 13).

The Mono Debris Dam (see cover illustration) was constructed on Mono Creek, which enters the Santa Inez River immediately above the original head of backwater of Gibraltar Reservoir. Because earlier experiences in California had shown that debris dams were subject to tremendous stresses during flood flows, it was considered necessary to build this dam of reinforced concrete. It is an Ambursen-type dam, 35 feet in height above stream bed, and 192 feet long. Its spillway is a center-overflow type, 16 feet in height above the original stream bed. It will discharge 20,000 second-feet. The original water-storage capacity back of the dam was 400 acre-feet. In the runoff seasons of 1936-37 and 1937-38, the basin was completely filled with dominantly coarse sediment. A survey made in 1938 showed that the dam had held back 624 acre-feet of sediment, extending from the spillway lip on a gradient of 0.395 percent to a point 2,785 feet upstream from the dam.

The Agua Caliente Debris Dam was completed in December 1937 on Agua Caliente Creek, which enters the Santa Inez River about 3 miles above the original head of backwater of Gibraltar Reservoir. It is a single arch-type, concrete dam, 65 feet in height above the original stream bed, and 240 feet long. The capacity of the center-overflow spillway is 5,000 second-feet. The original water-storage capacity of the basin was 310 acre-feet. A survey in November 1941 showed that 465 acre-feet of sediment had been detained by this dam.

The net amount of material held back by the two debris dams up to 1942 was 1,089 acre-feet, which is equal to 7.5 percent of the original capacity of Gibraltar Reservoir. These dams, although their cost was substantial, made possible within 5 years conservation of

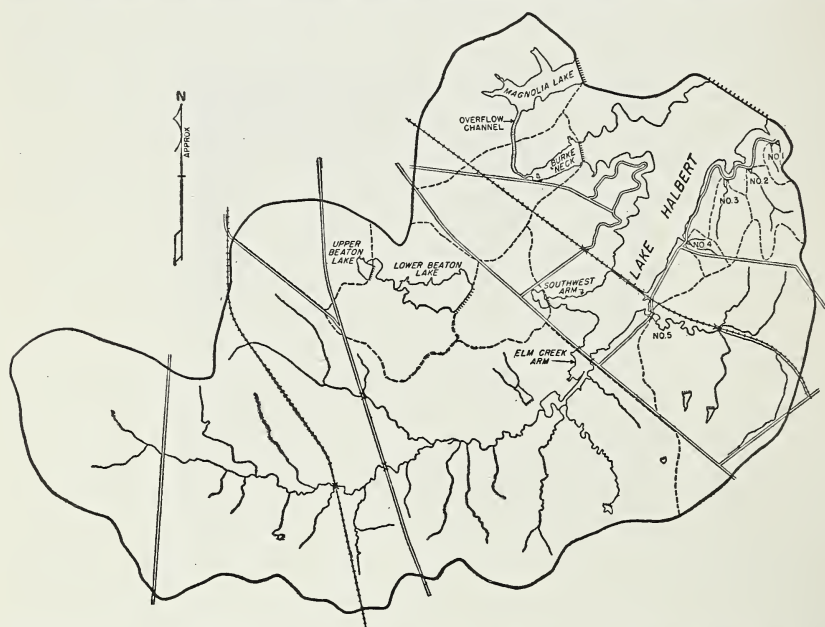


FIGURE 14.—Lake Halbert and drainage area at Corsicana, Tex., showing distribution of desilting basins.

storage space worth \$67,518 on the basis of the original cost of \$62 per acre-foot.

A number of much less elaborate settling basins have been built to protect Lake Halbert, source of water supply for Corsicana, Tex. (fig. 14). This reservoir was constructed in 1921 on Elm Creek, 3 miles southeast of Corsicana. The earth-fill dam, approximately 45 feet high and 2,780 feet long, created a reservoir with an original storage capacity of 7,350 acre-feet. The gross drainage area above the dam was 11.1 square miles, but this included the upper and lower Beaton lakes constructed on a tributary in 1895 with an aggregate capacity of about 428 acre-feet, and the old Burke Lake, the earliest unit of the city water-supply system, which was constructed on another arm about 1880, with a capacity of 131 acre-feet.

The Lake Halbert watershed lies within the Blackland Prairie and is gently rolling, with slopes averaging 3 percent. The soils range

from black clay to grayish-brown sandy loams. Approximately 75 percent of the land is devoted to agriculture, cotton and corn being the principal crops. Severe sheet erosion and shallow gullying are common on the agricultural lands.

In 1935 and 1936 a Work Projects Administration project was obtained by the city to raise the Lake Halbert Dam. The project also included raising Burke Lake Dam, now known as Burke Neck, which was thus made to form a more effective desilting basin on the north arm of the reservoir. The Elm Creek arm was largely cut off by a road fill, and under the bridge section a weir was built to further increase the desilting effect. The southwest arm was cut off at its head by a dam to form another basin. Five desilting basins were formed in the uncontrolled drainage area by construction of rock-fill and earth-fill dams. These dams and those on the main arms range in height from 4.5 to 9.75 feet and in length from 39 feet to 800 feet. Their drainage areas range from 10 to 3,000 acres. Several minor ponds above these basins also trap sediment. Except for small areas draining directly into the lake, the whole watershed is now controlled by desilting basins.

Reconnaissance measurements of sediment accumulated in all these basins were made in 1942. By assuming that the rate of sedimentation was constant in the reservoirs older than Lake Halbert, it was estimated that the basins trapped 21 percent of the sediment production of the drainage area since 1921, and that 79 percent had gone into Lake Halbert. The percentage trapped since the additional basins were constructed in 1936, however, obviously has been much larger. The estimated rate of sedimentation in Lake Halbert and the desilting basins combined is equivalent to 4.10 acre-feet per square mile of drainage area annually. This is one of the highest rates measured anywhere in the United States in a drainage basin of comparable size.

The cost of constructing or improving the eight desilting-basin dams was \$25,321. The original cost of Lake Halbert, exclusive of engines, pumps, pumphouse, pipe lines, and filter plant, was \$276,445. Raising the dam and constructing a road around the reservoir in 1935 cost an additional \$70,551.

Road fills were used to form settling basins at Mission Lake, constructed by the city of Horton, Kans., in 1924 as a source of municipal water supply. This reservoir, located on Mission Creek 0.7 mile northeast of the city, was shown by a sedimentation survey in 1937 (76) to have lost 15.6 percent of its original capacity of 1,852 acre-feet in 13 years. Its drainage area covering 9,984 acres is moderately rolling, contains silt loam and gravelly loam soils derived from glacial till, and is undergoing moderate to severe sheet erosion with considerable gullying near the lake. Seventy-seven percent of the land was in cultivation in 1937, wheat, corn, and hay being the principal crops.

In constructing roads around Mission Lake, it was necessary to make fills across seven minor tributary arms (figs. 15 and 16). The culverts in these road fills were set just above spillway level. Hence, water is ponded for some time before it overflows into the reservoir, and most of the sediment from these tributaries is deposited in the settling basins. A total of 2.32 acre-feet of sediment had accumulated in these settling basins at the date of survey. The aggregate drainage area of

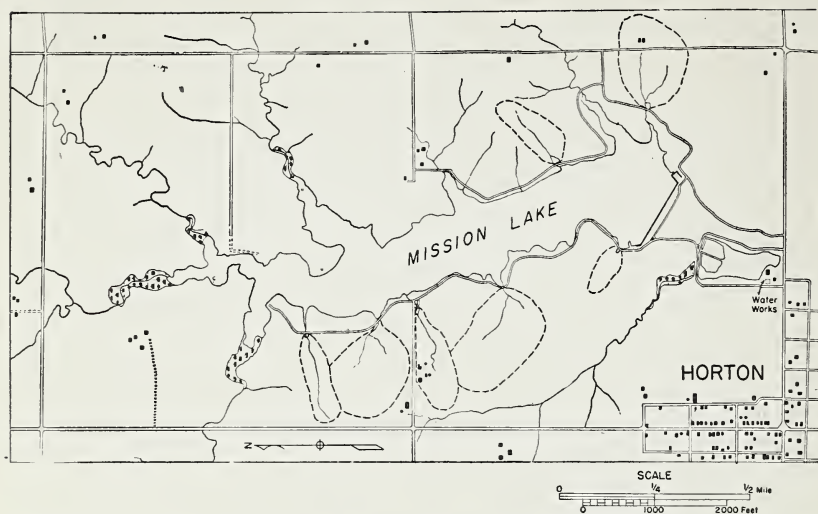


FIGURE 15.—Map of Mission Lake, water-supply reservoir for Horton, Kans. The dashed lines show the drainage basins above sediment traps created by road fills around the reservoir basin.

the basins is only 113 acres, or 1.13 percent of the total area. The sediment accumulated is 0.80 percent of the 289 acre-feet accumulated in the lake to 1937. If it were assumed that these minor drainage areas had the same rate of sediment production as the entire drainage basin, these road-fill dams were effective in holding back 71 percent of the sediment output from the controlled areas.



6644

FIGURE 16.—Typical settling basin behind road fill at Mission Lake, near Horton, Kans.

Large sediment-detention and water-impounding dams have been built some miles upstream from Zuni Reservoir, which has had a history of rapid silting. This reservoir, located on Zuni River near Black Rock, N. Mex., was completed in 1906 with an original capacity of 10,230 acre-feet at contour 990 (14,800 acre-feet at contour 998.3, which is the elevation of the top of the flashboards that control the present spillway level). Between 1906 and 1928 silting reduced the capacity at elevation 990 by 94.89 percent (116, p. 1696). This excessive rate of capacity loss was apparently due, first, to the small ratio of capacity to inflow, and, secondly, to severe erosion in the dominantly arid drainage basin.

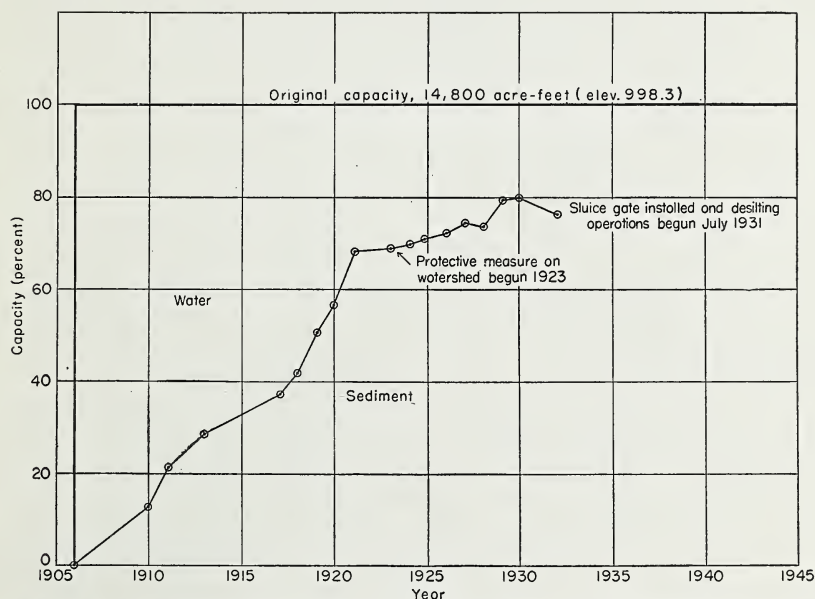


FIGURE 17.—Curve showing silting in Zuni Reservoir, near Black Rock, N. Mex. Note flattening of curve after 1921, attributed to protective measures in the drainage area, and increase of capacity after 1931, due to sluicing operations. (After Stevens.)

Attempts were made from 1923 to 1928 to control erosion along the stream channels above the reservoir by check dams and revetments. Data from silting surveys seem to indicate that these measures had some effect in reducing silting, as shown by the curve in figure 17, although the reduction may in part be due to differences in runoff, to greater sediment losses over the spillway, and to survey errors. In a report on his field examination of the Zuni drainage basin in October 1936, Rittenhouse notes that, due to inadequate maintenance, a large portion of these structures had been completely or partially destroyed.¹¹ In their place five sizable storage and sediment detention dams have been built above the reservoir in an effort to supplement the water supply and control silting in Zuni Reservoir below (see figs. 17 and 18.)

¹¹ RITTENHOUSE, G. THE EFFECTIVENESS OF DETENTION DAMS IN PREVENTING SILTING OF THE ZUNI RESERVOIR AT BLACK ROCK, NEW MEXICO. U. S. Soil Conserv. Serv., Sedimentation Division. 1936. [Unpublished.]



P-3827

FIGURE 18.—The drainage basin on Zuni Reservoir and watershed, McKinley and Valencia Counties, N. Mex., showing the location of debris and detention dams.

The upper or No. 3 Nutria detention dam, for example, was completed in December 1934 on the Rio Nutria about 3 miles above the lower Nutria Dam. It is approximately one-half mile long and 16 feet high and is constructed of earth. Its original capacity was about 1,500 acre-feet. The spillway is located between a bedrock knoll and the west side of the valley. A sluice gate near the west end of the dam releases water into a ditch that carries it back to the original arroyo some distance below. The Nutria No. 4 dam was built on a side tributary near the No. 3 dam in 1938, and a canal was dug connecting the new reservoir, which has a capacity of 878 acre-feet, with the older basin, so that the two now function as one.

Unquestionably the main detention dams have been effective in stopping and storing most of the sediment load delivered from the drainage areas above. Their history has shown, however, that maintenance must be provided in order to keep outlet works from clogging, and that overflow waters must be returned to the original channel bed over nonerodible slopes or structures. Otherwise, the amount of material eroded by the desilted waters may almost, or possibly more than, equal the amount of material caught by the dam.

Soil erosion is usually considered to be negligible in England, but even there, according to Rodwell (103, pp. 377-378), "catch-pits" or "debris-lodges" are employed in the control of reservoir silting. Such settling basins must be constantly inspected, however, by the "water bailiff" or his staff, particularly during or after periods of heavy rain, or following the occurrence of a sudden thaw, when masses of debris must be removed. Rodwell recommends (1) the installation of a draw-off pipe, (2) provision for easy access to each catch-pit by cart or truck to facilitate removal of debris, and (3) construction of the overflow weir at an acute angle to the direction of stream flow, not "square-on"—as is the more common practice. According to Rodwell, this plan permits a longer weir, affords an easier approach—particularly in a narrow valley—to the catch-pit, and results in stones and boulders being carried by their own momentum well forward to the end of the pit where they are the more easily removable.

Various types of settling basins built for purposes other than protection of reservoirs illustrate principles and designs that might well be applied to reservoir-silting control.

The Bennett irrigation and silting basin located near Wilsoncreek, Wash., was constructed to provide floodwater irrigation and to cause the deposition of a fertile silt on the valley soils (71). The basin is formed by the Nile Valley Dam, an earth-fill structure having a maximum height of 30 feet and a length across the valley of 925 feet. A concrete conduit with arched roof and vertical sides, 8 feet wide, 8 feet high, and 46 feet long, was built into the base of the dam. Water released through it is controlled by a wooden gate that can be raised or lowered from the top of the dam (fig. 12). This basin covered 345 acres and had a storage capacity of 2,903 acre-feet at crest stage when completed in 1918. Since that date floodwaters have been sufficient for nearly complete inundation each season except two. Water is usually impounded for about 2 weeks and is rather thoroughly desilted by the time it is released.

In addition to conserving water, which permits the harvesting of two or three crops of alfalfa seasonally and more than doubles the wheat yield per acre for this region, the basin caught 470 acre-feet of sediment up to 1936. The sediment had an average thickness of about 1.4 feet, or 1.8 feet on the parts of the basin used for cropland. The fertility of the sediment is markedly above that of soils of the surrounding drainage area as shown by both chemical tests and pot cultures.

Winsor (137) has described debris barriers or basins constructed since 1922 for flood control in Utah. Most of these basins are located on alluvial fans below the mouths of mountain canyons and were built mainly to protect towns and agricultural lands of the Salt Lake Valley region and adjacent parts of Utah from damage by debris deposition.

Figure 19, reproduced from Winsor's publication, shows the principal features of the type of settling basin most commonly constructed in Utah. The main conclusions drawn by Winsor from experiences in this State can be summarized as follows:

(1) The main dam at the lower end of the basin must be high enough to prevent overtopping by any flood.

(2) It is often more economical to build the dam initially to only sufficient height to provide for the first year's flood and to raise it after each period of significant deposition to a height sufficient to maintain a freeboard of 3 to 5 feet.

(3) The main dam and any side dikes should be built initially out of whatever material is available at the site.

(4) After the first period of deposition, the debris deposited in the basin should be utilized insofar as possible for raising the dam and side dikes, thus increasing the capacity of the basin.

(5) By means of diagonal barriers in the basin and intake channel, the floods may be diverted to first one side and then the other side of the basin so that their load may be deposited either uniformly, if this is desired, or in places easily accessible for its excavation as construction material.

(6) Diversion barriers within the basin may be constructed of trees and brush, of posts to which wire screen is attached, or of posts interwoven with willows and brush.

(7) The spillway in the main dam must be of sufficient capacity to pass the maximum flood flows.

(8) The spillway may be built of rubble masonry, concrete, rock-filled cribs, boulder mattresses encased in wire netting, or other similar materials.

(9) The elevation of the floor of the spillway should be such that a stilling pool will be formed above it to induce deposition of the fine debris.

(10) The best design for a spillway is bowl-shaped with the crest in a semi-circle and with the downstream wing walls bent into the arch of the crest, so that there is no marked line where crest or floor ends and wall begins; construction of this type is relatively stable and may be safely built on foundations generally considered insecure for masonry. Winsor (137, pp. 8-13) gives details of the design and construction of spillways.

Two debris basins near Nephi, Utah, cost about \$3,150, all of which was for labor except \$50. A debris barrier built across Salt Creek Canyon at the upper edge of Fillmore, Utah, cost \$1,500, most of which went for labor. A barrier constructed on Perry Creek cost \$2,200. A debris basin flood-control system on Pleasant Creek at Mt. Pleasant, Utah, cost \$8,000, 90 percent of which was for labor. The histories of these and other projects are given by Winsor (137).

In Los Angeles, Calif., and environs, 16 debris basins were constructed between 1934 and 1937 by the Los Angeles County Flood Control District and the United States Army Engineers. Most of these basins were excavated in alluvium near the apexes of alluvial fans and were designed to intercept the large volumes of coarse erosional debris that are carried out of small drainage areas on the excessively steep mountain fronts during flood runoff. The basins were considered, at the time of construction, to be emergency measures for the protection of the urban areas below until the mountain watersheds, largely denuded of their plant cover by recent fires, could be revegetated.

During the flood of March 2, 1938, these basins held back from 12,000 to 150,000 cubic yards of debris each, or a total of 689,000 cubic yards that otherwise would have been carried down to lower areas (fig. 20). The original cost of the 16 basins was approximately \$1,500,000. After the 1938 flood, an amount of debris approximately equal to that deposited during the flood was excavated from the basins at an average cost of about \$0.30 per cubic yard. Excavation was done by power shovel and trucks, which hauled the debris to the closest dumping areas, in most cases a fraction of a mile away.

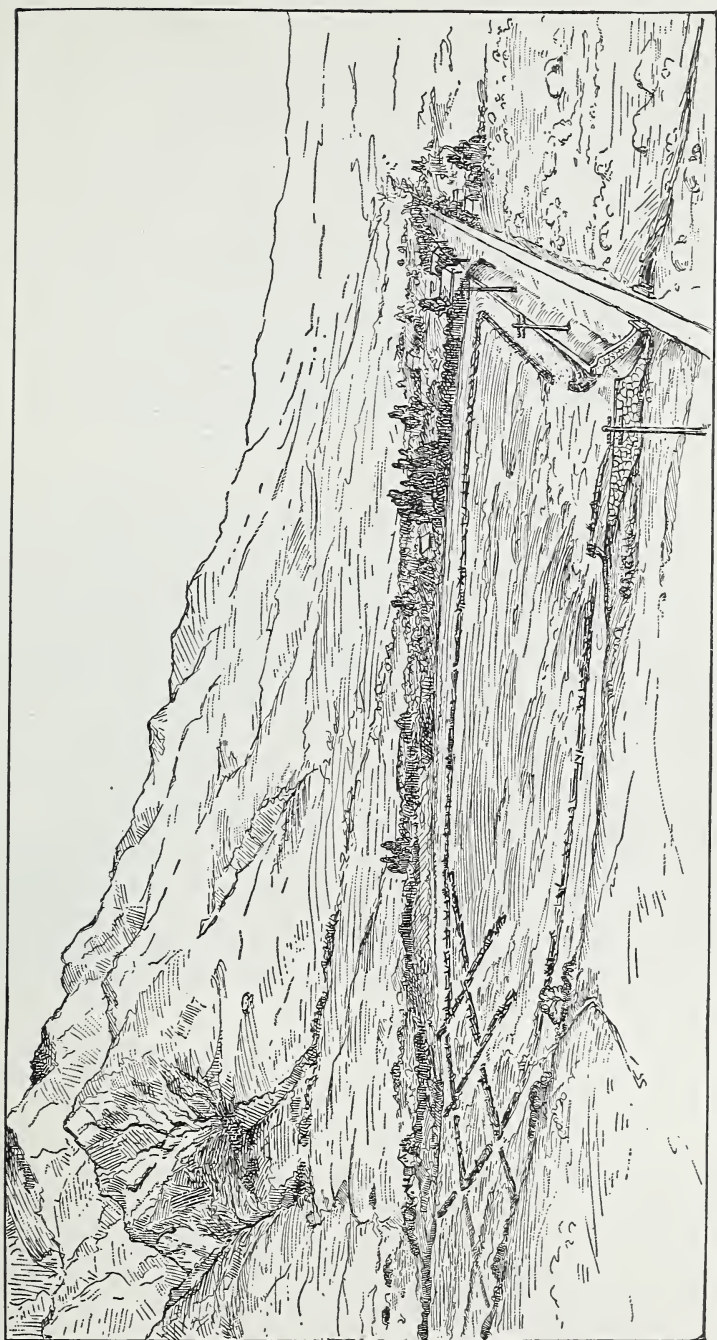


FIGURE 19.—Typical debris barrier for flood control at the foot of the Wasatch Mountains in northern Utah. (After Winsor.)

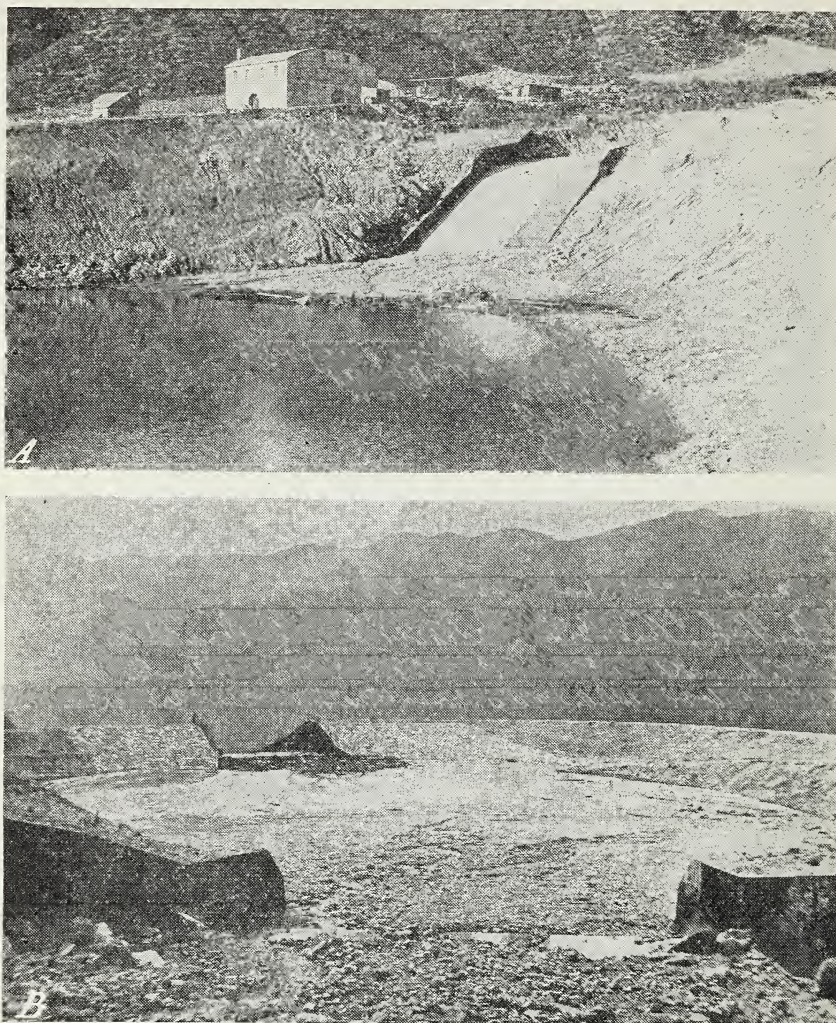


FIGURE 20.—Dunsmuir Debris Basin constructed by the Los Angeles County Flood Control District in the foothills of the San Gabriel Mountains above La Cañada Valley: *A*, debris basin on January 6, 1937; *B*, debris basin completely filled with sediment shortly after the flood of March 2, 1938. (Photo of figure 20, *A*, by Los Angeles County Flood Control District.)

Since the passage of the California Debris Act in 1893, which prohibited the sluicing of hydraulic mining debris into natural stream channels, numerous relatively small dams have been built to create settling basins for the storage of mining debris. Four major concrete debris storage dams on the Yuba, Bear, and American Rivers were authorized by Congress at an estimated cost of \$6,945,000 in 1935 as an aid to the resumption of hydraulic mining (13).

Settling basins have been used in many parts of the country to protect drainage ditches and irrigation canals against excessive silting.

An example of this type of basin from Doniphan County, Kans., has been described (29). In June 1917 erosional debris carried by heavy storm runoff out of the Chase Creek watershed (fig. 21) caused severe damage to drainage ditches and farm land in the Missouri River bottoms. This led to organization of a drainage district and construction of a debris basin at the mouth of Chase Creek.

The "old debris basin," as it is titled in figure 21, covered 26.6 acres and was enclosed by a dike 6 feet high. Between 1920, when the basin was completed, and 1930 it was filled with sediment to an average depth of 5 feet, or by a volume of 135.6 acre-feet, all from the 1,011-acre Chase Creek watershed. A "new debris basin," which was still functioning in 1937, was then constructed on the west side of the mouth of the creek. The old basin has been used for farming both before and since its abandonment. Corn yields of 65 to 80 bushels per acre have been obtained in most years compared with about 40 bushels per acre on adjacent alluvial land.

The rental cost of land in the basins from 1920 to 1937 amounted to \$12.70 per acre of drainage area contributing to them. The cost

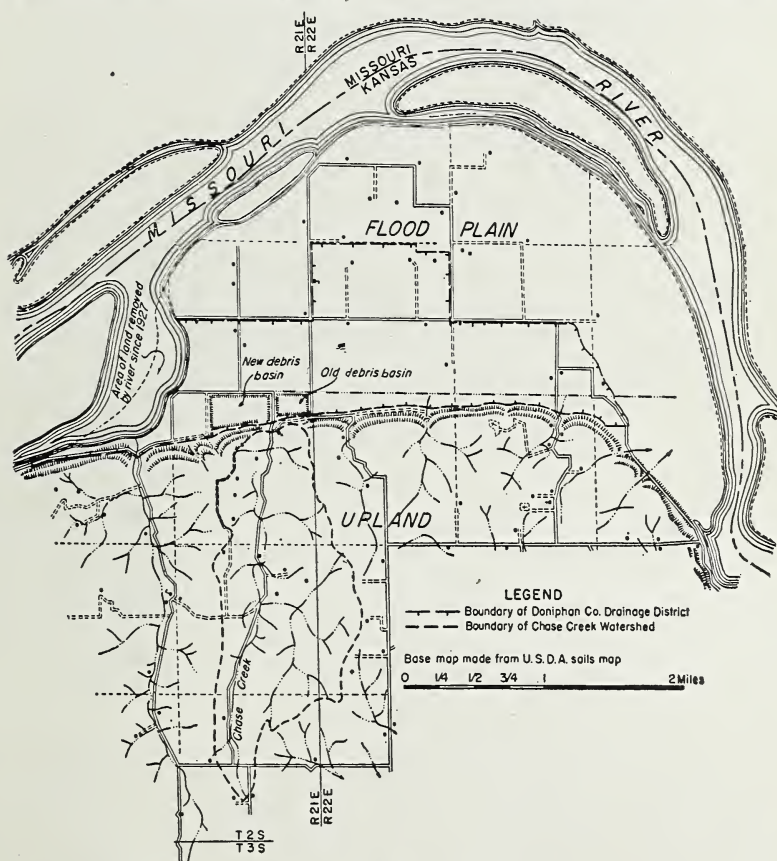


FIGURE 21.—Map showing location of debris basins constructed to protect drainage ditches of the Missouri River flood plain from the sediment output of the Chase Creek watershed in Doniphan County, Kans.

of a complete erosion-control program with adequate maintenance would have been less, judging from programs completed in similar drainage areas in this region. A conservation program not only would have accomplished substantially the same result in the bottom lands, but would also have sustained productivity of the 1,011 acres in the drainage area by prevention of most of the soil loss of 24.5 tons per acre during this period.

Towl (120, pp. 343-344), who has described the settling basins constructed since 1915 by various drainage districts in Nebraska, Iowa, and Missouri, expressed the opinion that settling basins need not be designed with spillways and outlet structures to impound water but need be only broad flats where the flow is forced to spread and lose velocity. If, however, the stream has a watershed of 10 square miles or more, a pick-up ditch or lateral should be provided at least one-quarter mile away from the point of inflow. In this distance, Towl believes, all silt that would deposit in a drainage ditch will have been

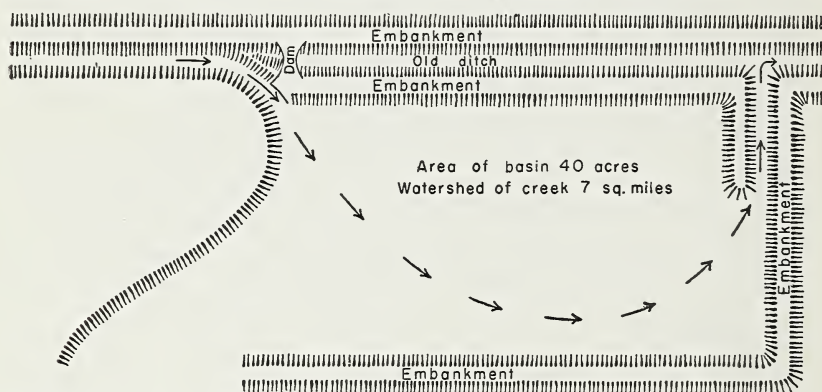


FIGURE 22.—Hill Creek Desilting Basin beside a drainage ditch near Herman, Nebr. (After Towl.)

deposited in such a spreading basin. Figure 22 illustrates his theory as applied in the Hill Creek Basin at Herman, Nebr.

Towl also makes the point that such basins may be cultivated during the time they are functioning, if the farmer is willing to take the risk of inundation of the crop. They are often considered especially valuable after they have filled with deposits. The raised land surface of these basins is not only flood free, but the newly made soil may be exceptionally productive with proper husbandry. This was exactly the situation that developed in the Doniphan County, Kans., basin. Ashe (16, pp. 15-16) also advocated the use of settling basins for farm land after they had served their original purpose.

Fixed mechanical or hydraulic devices for removing and automatically disposing of the sediment have been used in conjunction with several types of settling basins. Such devices require, however, either that the reservoir be located off the main channel so that the material removed can be sluiced back into the stream, or that sediment disposal canals or conduits be constructed around or under the reservoir. Basins involving these special features are described on pages 51-64.

Appraisal.—Settling basins generally cost more per unit of storage than the reservoirs they protect. Therefore, in most cases, it would

seem unwise to adopt a plan of using settling basins as a primary method of silting control at the time a new reservoir is built. Ordinarily a much larger volume of sediment storage could be obtained at a lower cost by raising the reservoir dam a few feet. Specific exceptions are numerous, however: (1) Physical conditions may prevent building a higher dam. (2) Topographic conditions and the supply of local construction materials may be favorable for the development of settling basins at unusually low cost compared with increasing the size of watertight impounding dams. (3) Road fills, required for other purposes, often may be utilized as settling basins at small additional cost. (4) The commercial sale of sand and gravel may more than pay for the cost of construction and maintenance of settling basins. (5) Under some conditions the land can be sold for farming after being built up. (6) Often it is desirable to hold back sediment from a new reservoir while a program of erosion control on the watershed is being developed.

The feasibility of settling basins by no means should be overlooked in planning the protection of a new reservoir.

The problem is often different after the reservoir has been built. If a silting investigation discloses a high rate of storage lost, immediate protection may be essential. Other methods of sediment control, such as the installation of sluicing gates or the purchase of dredging equipment, may be found to be too costly. Still other methods may not become effective as rapidly as necessary. If an abrupt change in watershed conditions is caused by fire, hydraulic mining, or construction activities, which cause an unusual amount of debris to enter the streams, debris basins may be needed until conditions can be stabilized.

When locating and constructing debris dams, the possibility of raising the main reservoir dam at some future date must be kept in mind. The maximum level to which the main dam might be raised should be ascertained and settling basins should be placed far enough upstream, if possible, to be above this level. Otherwise, the effect of withholding debris from the present reservoir area will be entirely lost when the future water level will be above the elevation of the debris barriers.

Where roads have been constructed around a reservoir, or where embankments or dams of any kind already exist above a reservoir, these fills should be investigated as possible barriers behind which sediment can be trapped and stored cheaply. Where use of such barriers entails little additional cost, or where the basins could be paid for by the agricultural value of made land, or by sale of material removed from the basin, it would appear worthwhile to develop them in addition to, or regardless of, other measures of sedimentation control.

From a long-range point of view, settling basins must be considered as purely temporary expedients, useful principally to control the movement of sediment into the reservoir until some better and more permanent means of silting control can be effected. The cost of debris basins may be based, however, on the value of the deferred cost of replacing the useful storage that they will conserve, plus any values created by the basin, rather than on the original cost value of the existing storage.

VEGETATIVE SCREENS

Vegetative screen is a term used here to mean a dense growth of vegetation through which sediment-laden water must flow to enter a reservoir. The purpose, as well as the effect of such screens is to diffuse or spread the flow of water, reduce its velocity, and cause the sediment to deposit around and between the plants. To make an effective screen the vegetation usually must cover the original channel area, as well as the flood plain of the inflowing stream, but if the channel is so small that above-normal flows are forced overbank then vegetation on the flood plain alone may be sufficient. The vegetation best adapted for this purpose would be (1) deep rooted to prevent its being scoured out if swift currents develop, (2) small stemmed with plants capable of growing very close together, (3) tough and fibrous rather than brittle, (4) low-growing with foliage preferably reaching to the ground level, (5) resistant to drought and inundation, and (6) non-palatable to stock.

The best known example of a vegetative screen in this country is the growth of tamarisk (saltcedar)¹² along the Pecos River above Lake McMillan, north of Carlsbad, N. Mex. The original Lake McMillan Dam was completed in 1894 by the Pecos Irrigation District and created a reservoir having a capacity of approximately 32,500 acre-feet at spillway elevation 3,258.9 feet. After the dam was breached by floods in 1906, the irrigation project, including Lake McMillan, was taken over by the United States Bureau of Reclamation, and the spillway elevation has since been changed several times. At its present elevation the original capacity would have been about 90,000 acre-feet. Figure 23, modified from Stevens' figure (113, p. 212), shows the progressive storage capacity loss by silting. The significant feature of the

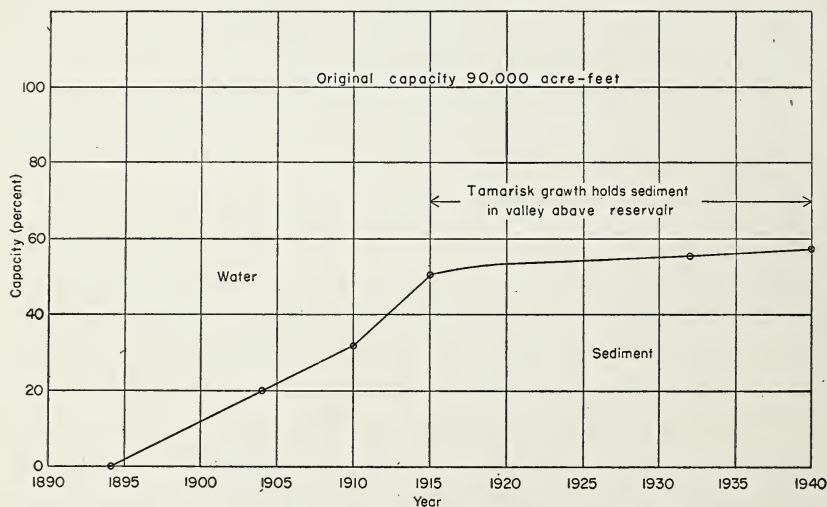


FIGURE 23.—Curve showing silting in Lake McMillan on the Pecos River, near Carlsbad, N. Mex. Flattening of the curve after 1915 is attributed to the effect of tamarisk growth in the valley above the head of the reservoir. (After Stevens.)

¹²The tamarisk now growing wild in valleys of the West probably includes both *Tamarix gallica* and *T. parviflora*, but other species only rarely, if at all.

curve is the decided flattening after 1915. This has been explained by Walter (116, pp. 1721-1725) as a result of dense and extensive growths of tamarisk at the upper end of the lake, which have caused a spreading of the river flow above the reservoir, resulting in velocity reduction and sediment deposition. The silting problem, which was once considered serious at Lake McMillan, has been materially lessened by the accidental introduction of this foreign evergreen shrub or small tree.

Tamarisk was originally a native of the Mediterranean region, Western Asia, and India. Its somewhat showy pink and white flowers present an attractive appearance during the blooming period, and for this reason it was brought into this country for use as an ornamental shade tree. Tamarisk trees were planted in the Pecos River Valley many years before they appeared near Lake McMillan. According to



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FIGURE 24.—Typical dense growth of tamarisk in the Middle Rio Grande Valley near Bernardo, N. Mex.

Walter, a clump of rather large trees was growing along the river east of Roswell, about 60 miles above Lake McMillan, some time prior to 1912, when the first tree was noticed at the upper end of the reservoir.

The entire upper end of the reservoir, except for a few narrow channels, has been covered with a dense growth of tamarisk for the past 20 years (a comparable growth in the Rio Grande Valley is shown in fig. 24). The tamarisk growth now extends several miles upstream above the original head of backwater and covers most of the mile-wide flood plain.

When water stands around the plants for more than a week they usually die, but revegetation begins immediately after the water drains away. In many places the growth is so dense as to be almost impenetrable. The plants range in height from more than 20 feet down to 1 foot or less, and in diameter from the size of a pencil to 6 or 8 inches. This dense growth, together with the dead brush and litter, has caused deposition of 5 feet or more of sediment at the upper end of the lake and upvalley.

Walter (116, pp. 1721-1725) has reported that during the summer of 1926 the Middle Rio Grande Conservancy District planted some of the Lake McMillan tamarisk in the Rio Puerco Valley above Socorro, N. Mex., in an attempt to solve the sedimentation problem of the lower Middle Rio Grande Valley. Some of the plants were alive in the fall of 1927 and bore seed pods, but the pods contained no seed. Tamarisk trees, 30 feet high, are growing in Albuquerque, N. Mex., but, according to Walter, have never been known to produce seed. However, reproduction by seed takes place farther down the Rio Grande, in the vicinity of El Paso, Tex. Seedlings do not produce seed until about the third year. These observations indicate that soil or climatic conditions probably have a decided effect on reproduction of tamarisk by seeding.

Taylor (117, pp. 149-150) reported in 1930 that a thick growth of tamarisk about 3 years old, with plants ranging from 18 inches to 7 feet tall and up to 3 inches thick, was spreading rapidly on a flat 2 miles long by 1 mile wide at the upper end of Lake Kemp in Wichita County, Tex. Growth was beginning in other shallow areas all around the lake. While heavy silting was taking place at the head of the lake, the water was relatively clear after passing through the vegetated area. Little silting was reported more than 3 miles below the head of the lake.

Taylor pointed out that tamarisk may cause considerable trouble when it spreads to irrigation canals and that "perpetual care and watchfulness will have to be maintained to prevent clogging of the canals and a consequent reduction in the carrying capacity."

Bennett (22, p. 547) has noted that it is frequently possible to control or minimize silting in small ponds by establishing a grass filter immediately above them. This has been accomplished successfully in the Southwest by excluding stock from a suitable segment of land across the drainage depression a short distance above the pond.

Sedimentation has also been induced in various parts of the world, notably the Federated Malay States and Burma, by constructing training fences of poles across flood plains subject to frequent overflow (65, pp. 107-109). These fences reduce the current velocity and cause deposition. They may be an effective aid in the establishment of vegetative screens.

Appraisal.—Vegetative screens are unquestionably effective in reducing the rate of silting of reservoirs if flood waters are forced to pass through them before entering the lake. Their use in any particular locality depends on (1) the availability of extensive areas, generally flood plains, of relatively cheap or worthless land, on which vegetation can be planted, (2) health and other hazards that might be created by almost impenetrable tracts of swampy lands, and (3) the discovery or adaptation of plant species, such as varieties of fast-spreading shrubs, that will meet the requirements of defective screening, will withstand the usually harmful effects of mud and water, and are suited to the climate.

Thus far no vegetative screens comparable with those of tamarisk have been described. It is known, however, that in the southeastern part of United States densely growing willow shoots, supplemented by other types of water-loving trees and shrubs, do have an effect on inducing deposition in valleys above the heads of reservoirs. An

important field of botanical research exists here in discovering useful species. Until such research is conducted it would seem advisable, in locations where valley flats above a reservoir may be available, to consider planting those types of native vegetation that most nearly fulfill the requirements of being deep rooted, or having thin, flexible stems and low-growing foliage, and of spreading rapidly.

If channels are deep and not easily vegetated it may be desirable to construct a dam or dams up to bank height in order to force flood flows out over the flood plains and through the vegetation.

Vegetative screens bring up the same problem as do settling basins with respect to future raising of the dam. If all sediment deposited in an area of vegetation immediately above an existing reservoir is within the storage area of an enlarged reservoir, then the preservation of present storage would mean only a loss of future storage. Another caution to be observed is that the propagated vegetation is not of a type whose spread to other developments, such as canals or farm lands, would be detrimental to their use and maintenance.

OFF-CHANNEL RESERVOIRS

An off-channel reservoir is considered here as a reservoir that is developed in any location other than on the stream that is the principal source of water supply for that reservoir. In regions of well-developed drainage, off-channel reservoirs are sometimes constructed on tributary streams above their junction with the main stream. In arid regions they are frequently developed in broad valley flats, bolsons, or swales that receive little or no natural drainage. Off-channel reservoirs are filled with water through canals or conduits leading from a diversion dam on a main stream.

Off-channel reservoirs are useful for silting control only where the entire flow of the main stream cannot or does not need to be stored. In the Western States that have laws governing the priority of water rights, often only a part of the total stream flow can be stored in any reservoir. Even if rights permit storage of the entire flow it is often economically infeasible to construct reservoirs of sufficient size to accomplish this purpose. In the Eastern States, reservoirs are seldom built of sufficient size to store the entire annual runoff, and most of them waste many times as much water over their spillways as they store during the course of the year.

Off-channel reservoirs are advantageous in controlling sedimentation because flood flows carrying large burdens of sediment need not be diverted into feeder canals leading to the reservoir but may be passed on downstream at the diversion dam. Even if part of the flood flow must be diverted to fulfill water needs, this diversion may often be started after the peak of the flow has passed. It is well known that the greatest concentration of suspended sediment occurs in the earlier stages of a flood flow and that the peak of the suspended load is usually well ahead of the peak of flow. (See p. 74 and fig. 34.)

Another advantage of off-channel reservoirs is that settling basins or desilting works can often be installed advantageously at the diversion dam or along the line of the canal leading from it to the storage reservoir. Hence, with relatively little loss of the diverted water, a considerable part of the sediment burden of the diverted flow may be

flushed back into the main stream. This practice, however, has been known to cause serious channel aggradation below the diversion dam, so that this problem should be investigated when considering such a plan.

Most of the off-channel reservoirs in this country have been so located either because water storage could be obtained in such locations at a smaller per-unit cost than in reservoirs constructed on the main stream, or because no suitable dam sites or reservoir basins existed on the main stream.

Several Federal irrigation projects in the West include off-channel storage reservoirs as the principal features of the water system.

On the Umatilla project in northeastern Oregon, the Cold Springs and McKay Reservoirs, which together have a capacity of 125,000 acre-feet, are fed by a 24-mile diversion canal from the Umatilla River, whose mean annual runoff is 520,000 acre-feet. These reservoirs were located off-channel in minor drainageways because no suitable dam sites were considered to exist in this reach of the Umatilla River.

Among the non-Federal irrigation projects that include an off-channel reservoir is the Reeves County Water Improvement District No. 1 in western Texas. Water for this project is stored in Balmorhea Reservoir, 1 mile southeast of Balmorhea, Tex. The reservoir basin is created by a dam across a broad swag, which carries little natural runoff. When completed in 1915, the reservoir had a surface area of 529 acres and a capacity of 6,155 acre-feet. It is fed by a diversion canal about 5 miles long, extending from a diversion dam on Toyah Creek several miles west of Balmorhea. The drainage area above the diversion dam is 244 square miles, whereas an area of only 15 square miles drains directly into the reservoir. The intake canal, as originally constructed, ended about 1 mile from the reservoir. Prior to 1932, the water flowing out of this intake canal spread across the broad, smooth slope leading down to the reservoir and, filtering through a dense growth of mesquite, shrubs, and grass, lost most of its sediment load before reaching the reservoir. In 1932 the rainfall was more than double the normal average of about 14 inches, and so much water passed through the intake canal that it excavated a channel 6 to 9 feet deep and 80 feet wide from its former end to the reservoir. Most of the sediment now in the lake is believed to be the material eroded from this channel. A reconnaissance survey of sedimentation in August 1940 indicated that the lake had lost approximately 9.3 percent of its original capacity. Except for this unfortunate channel erosion, the lake would doubtless have been comparatively free of sedimentation for many years to come.

Another non-Federal project is the Horse Creek Reservoir, located in a depression between Horse and Adobe Creeks about 3 miles north of the Arkansas River in Otero and Bent Counties, Colo. It was constructed in 1900 and was first connected by canal with the Arkansas River in 1910 and with the Horse Creek drainage area in 1916. A sedimentation survey made in 1940 showed that the reservoir had lost 15.12 percent of its original capacity of 36,203 acre-feet in a period of slightly more than 39 years. The amount of water diverted into the reservoir during this period was 500,906 acre-feet from the Arkansas River and 64,012 acre-feet from Horse Creek. Sediment meas-

ured in the feeding canals and that measured in the reservoir totaled 6,519 acre-feet. Of this amount an estimated 460 acre-feet was derived from the Horse Creek watershed and the remainder from the Arkansas River. Thus the percentage of sediment to inflow from the Arkansas River was about 1.21 percent by volume. If the average annual flow of the Arkansas were assumed to contain the same percentage of sediment, a reservoir of the same capacity as the Horse Creek Reservoir developed on the river would lose 15 percent of its capacity in 1 year rather than 39 years.

The location of water-supply reservoirs off channel not only reduces the rate of capacity loss by silting but often results in material savings in the cost of filtering out the sediment in the purification of the water supply.

Dalecarlia Reservoir of the Washington, D. C., water-supply system is an off-channel reservoir impounded on Little Falls Branch and other minor tributaries just north of the Potomac River on the boundary line between Maryland and the District of Columbia. It is fed by a conduit from a diversion dam at Great Falls some 9 miles up the Potomac River. The purpose of the reservoir is to equalize the water supply and provide initial clarification of the water by keeping it in storage before it is released to other storage basins and the filtration plant.

Beginning in March 1906, the practice of controlling diversion was instituted at Great Falls in an effort to reduce the amount of sediment reaching Dalecarlia Reservoir. According to Hardy (66, p. 304) the Potomac River is subject to rapid fluctuations in turbidity, which is largely a reflection of the content of very fine particles of clay in the water. It is not uncommon to have a turbidity of 100 p. p. m. one day, and 1,000 p. p. m. the next. The high turbidity usually disappears about as rapidly as it comes and is seldom higher than 500 p. p. m. for more than 5 days at a time. Frequently, however, a succession of waves of high turbidity will appear so close together that the effect of one has not disappeared before another is felt.

After 1906, when the river water became excessively turbid, the control gates to the conduit were closed, and the muddy water was allowed to flow over the diversion dam while the city was supplied from the water stored in the Dalecarlia and two other storage reservoirs.

Based on the turbidity measurements at Great Falls Dam and at Dalecarlia Reservoir, calculations were made by the United States Army Engineers of the approximate amounts of sediment excluded from the reservoir during the period from March 1906 through June 1920. These data, taken from the annual reports of the Chief of Engineers, United States Army, are shown in table 1. It is noteworthy that by excluding water from the diversion conduit during periods ranging from 3.4 to 34.8 percent of the time during the respective years, 21 to 60 percent of the sediment that otherwise would have gone into the reservoir was successfully diverted and passed on downstream. Thus the cost of maintaining the storage capacity of this reservoir by dredging was materially lessened.

Even where a large part of the stream flow must be diverted into an off-channel reservoir, it can be protected by installation of desilting works at the diversion weir or in the intake canals.

The best known desilting works in this country, although installed to protect irrigation canals rather than a reservoir, are those recently

TABLE 1.—*Sediment excluded by controlled diversion from Dalecarlia Reservoir, Washington, D. C.*

Period	Estimated sediment that would have reached reservoir without diversion control	Proportion of time during which water was excluded from intake conduit	Sediment diverted	
	Tons	Percent	Tons	Percent
1906 ¹	7, 177	7. 79	3, 264	45. 48
1906-07 ²	8, 457	5. 15	3, 571	42. 23
1907-08.....	9, 586	5. 27	3, 684	38. 43
1908-09.....	6, 092	7. 64	1, 899	31. 17
1909-10.....	6, 522	10. 50	2, 613	40. 06
1910-11.....	3, 102	11. 26	1, 403	45. 23
1911-12.....	16, 979	21. 15	5, 142	30. 28
1912-13.....	12, 873	16. 62	3, 772	29. 30
1913-14.....	11, 251	20. 27	4, 950	44. 00
1914-15.....	14, 697	22. 82	3, 165	21. 54
1915-16.....	19, 815	34. 81	6, 643	33. 53
1916-17.....	22, 338	12. 36	9, 276	41. 53
1917-18.....	26, 305	14. 96	15, 736	59. 82
1918-19.....	12, 808	10. 32	7, 706	60. 17
1919-20.....	6, 644	3. 39	2, 153	32. 41

¹ March through June.² July through June, same for all succeeding periods.

constructed at the heading of the new All-American Canal at Imperial Dam on the Colorado River in California. As described by Forester (54), these desilting works consist of six settling basins arranged in pairs (fig. 25). Each basin is approximately 269 feet wide and 769 feet long and has an average depth of 12.5 feet. The basins are set at an angle of 68° with the inflow channels. Each basin has a rated flow capacity of 2,000 second-feet and each pair of basins is fed by an inflowing channel of diminishing cross section located between the basins. Water from the concrete influent channel is distributed uniformly to the two basins by flowing through vertical slots of special design in the walls of the channel. The water flows across the basin to an effluent channel leading to the main channel of the All-American Canal. The effluent channels may also be operated to bypass the water around the settling basins when there is no need for desilting. The maximum velocity of flow across the basins is 0.22 foot per second. At this velocity the detention period is 21 minutes. It is estimated that with this velocity approximately 80 percent of the maximum incoming sediment will be deposited on the floor of the basin. The design of the basins is based on a total inflow of 12,000 second-feet, or 80 percent of the capacity of the canal. The average sediment load for a flow of 12,000 second-feet was estimated to be 60,000 tons dry weight per day.

The sediment deposited in the basins during the passage of water from the influent to the effluent channels is removed mechanically and as a continuous operation by means of 72 rotary-type scrapers, each 125 feet in diameter. These move the deposited sediment into collecting trenches from which it is forced into system of sludge-disposal piping, and thence into the sluiceway channel that carries it back into the river below. Provisions have been made in the design of the desilting works for additional units, should they be required at a later date when the diversion is increased to the maximum capacity of the All-American Canal. The cost of the initial installation, aside from the diversion dam, head gates, and canal, was about \$3,500,000.

Desilting works constructed in 1936-37 as a part of the Columbus Project of the Loup River Public Power District, Columbus, Nebr., consists of a settling basin 10,000 feet long and 200 feet wide at the bottom, which provides for a maximum water depth of 14 feet (27). This settling basin is at the head of the canal which leads from a low weir across the Loup River to the Monroe power plant and thence to the 11,000 acre-foot Babcock Reservoir, an off-channel regulating reservoir 3 miles north of Columbus, where another power plant is located, and where the canal flow returns to the river.

Water is drawn into the settling basins through intake gates over a low skimming weir, which has a sill elevation above channel bed to



FIGURE 25.—Desilting works at the head of the All-American Canal, Imperial Dam, Calif. (Photo by U. S. Bureau of Reclamation.)

prevent entrance of most of the bed load. The canal intake is adjacent to a 250-foot-long scouring section of the main river weir, which is provided with three deep Tainter gates and was designed to prevent bed rise in front of the canal intake structure. At the lower end of the settling basin is a second skimming weir. A useful flow of 3,500 second-feet can be diverted through the settling basin at a velocity of only 1.30 feet per second, half that of the canal beyond.

Sediment deposited in the settling basin is removed by an electrically driven floating dredge equipped with a 28-inch centrifugal pump driven by 1,200-horsepower motor. Tests have demonstrated that this equipment can remove 1,200 cubic yards of sediment per hour. The discharge is carried through 30-inch steel pipe and deposited at intervals along the river bank where it is carried away by flood waters. The construction cost of the desilting works, exclu-

sive of right-of-way, was \$590,000. As power for operation of the dredge is used in off-peak periods its value is estimated at only about one-half mill per kilowatt hour.

The Loup River carries up to 5 percent by volume of sediment. Operating experience with the desilting equipment has shown that the annual sediment deposit in the settling basin is approximately 2,300 acre-feet, of which 80 percent is bed-load sand that is deposited in the upper part of the basin. This sand constitutes 0.20 percent of the volume of river water diverted. The average volume of suspended silt and clay in the river water is 0.14 percent, of which 0.04 percent is deposited in the basin, 0.01 percent in the canal system, and 0.03 percent in the reservoir, and 0.06 percent is carried through the whole system without deposit.

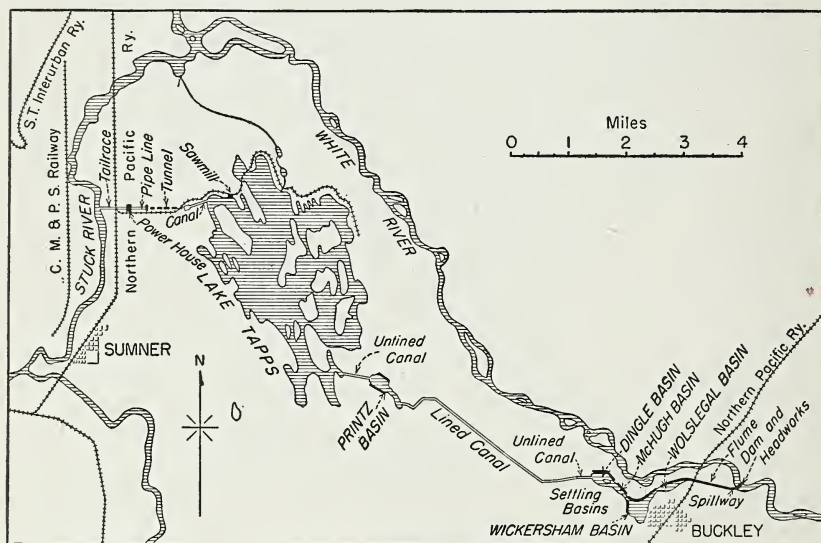


FIGURE 26.—Map of the White River power development near Sumner, Wash., showing the off-channel Lake Tapps and the several settling basins in the intake canal.

A number of older power and irrigation developments have been provided with desilting works. In the White River power development near Sumner, Wash. (3), a chain of settling basins 2 miles long was constructed in the canal leading from the diversion dam on White River near Buckley to the off-channel Lake Tapps, which holds storage for the power plant. These basins were to serve the dual purpose of deposition of heavy sediment and of storing water to increase secondary power generation. Sluice gates in the settling basins permit sluicing out the accumulated sediment with the use of only a relatively small part of the water that passes through the canal. Figure 26 illustrates the arrangement of these settling basins with respect to the diversion dam and off-channel reservoir.

Basel (19) has described the desilting basin in the diversion canal at the hydroelectric plant on the Kern River, Calif. This settling basin is 3,200 feet long by 400 feet wide by 10 feet deep and will hold 5.7 acre-feet of sediment below the grade of the channel and 91.8 acre-

feet of water. The basin is formed by an artificial embankment, or dike, riprapped with rock on the outer slope and puddled with clay and is designed to keep sediment out of the canal leading to the hydro-plant.

Evans (50) has described the desilting works at the Tacoma hydroelectric power plant, which receives its water supply from the Nisqually River in Washington. Seigfried (109) and Harisberger (67) have described desilting devices used at other power projects in the Pacific Northwest. Mathewson (88) has described sand traps used in hydroelectric plants in South America. In an anonymous article (9) a description is given of a Swiss method of clarifying water and removing sand, which has been adopted in some Italian hydroelectric works. Most of the desilting works at these hydroelectric plants were designed to keep coarse sediment from reaching the turbines, which are seriously damaged and must be frequently replaced if subjected to abrasion by sand transported by water under a high head.

Newell (93) has described a concrete-lined sand trap 28 by 40 by 8 feet in size built at a cost of \$5,619 to keep sediment out of the Notus Canal on the Boise irrigation project in Idaho. Parshall (96) has described the Parshall sand trap for the removal of bed load from irrigation and other channels. Bharadwaj (25) has described Indian methods for preventing sediment deposition in channels, which are also applicable to exclusion of sediment from canals leading to off-channel reservoirs.

The problem of controlling silting in canals has probably been studied more extensively in India than anywhere in the world. The many reports on this subject by the governmental agencies of India are well worth consulting.

Appraisal.—The construction of off-channel reservoirs should be seriously considered (1) if sites providing requisite storage are available in valley flats or on side drainages within a few miles of the stream from which the water supply is to be obtained, and (2) if it is not necessary to store the entire flow of the main stream. The reduction in silting that may be achieved by locating reservoirs off the main channel will be governed (1) by the ratio of water that must be stored to the total flow of the main stream, and (2) by the periods of the year during which storage must be available with respect to the flow characteristics in the stream. It seems reasonable to anticipate that a reduction of at least 25 percent in the rate of silting might be effected by locating the reservoirs off the main channel. A reduction of 50 percent should not be uncommon; and where the ratio of storage required to the total flow is small, particularly where the low-water or base flow of the stream alone is sufficient, the reduction in silting rate may well be 90 percent or more. If adequate desilting works are added to the project, the reduction in silting should range from 50 to 90 percent, even when most of the stream flow is diverted.

If suspended-load records of several years' duration on the main stream can be obtained, or even if such records are available for adjacent and similar basins, it is possible to calculate the approximate sediment load that would be diverted into canals with the amount of water required to supply storage needs. In making such calculations the higher discharges and earlier stages of flood flows would be first eliminated, and with them the quantity of sediment that they trans-

port. Successively lower flows would be eliminated until a point was reached where all of the remaining flow would have to be diverted. The sediment load of this remaining flow could be calculated, and its percentage to the total suspended load transported by the stream would give a measure of the benefits in reduced sedimentation. Generally, material moving as bed load in the main stream can be prevented from entering the canal.

Off-channel storage projects generally cost more per unit of storage obtained than reservoirs developed on the main stream, but unfavorable topography or lack of dam sites on the stream may reverse this condition. The additional expense of constructing diversion dams and diversion canals or conduits from the main stream to the reservoir may be offset by the smaller cost required for the main dam, which does not need to pass flood flows.

BYPASS CANALS AND CONDUITS

In this section are included those schemes that involve the diversion of sediment-laden flows through canals leading around, or through pipes laid under, a reservoir located on a main stream channel. The various methods all require the construction of some type of diversion dam or weir at the head of the reservoir basin.

As early as 1900, Lippincott (*85, p. 41*), in discussing the storage of water on the Gila River, suggested that when all water available in a given drainage basin is required for irrigation, and when the reservoir built to store this water has reached a dangerous silting condition, a "large storm channel" should be constructed around the reservoir above the maximum flow line. As much water as possible should be passed through this canal for direct irrigation downstream. The canal should have a large cross section in the upper part of its course, and a reduced section in the lower part. Spillways should be located at the side of the canal where the sections change in dimension. The excess water thus carried down the canal would be skimmed from the top of the flow into the reservoir below. The larger part of the sediment, however, would travel on down the canal.

Hughes, discussing this proposal in an appendix to the Army Board's Report (*123, pp. 149-150*) on San Carlos Reservoir, concluded that (1) the high-level marginal canal remained attractive partly because it would divert some sediment, and partly because it would provide during much of the time a higher and more constant head for generation of power than would the fluctuating reservoir level; (2) an improvement would be to make the canal several times as large as originally proposed, to carry even the smaller floods, and to provide for escape of excess water with its sediment load into the lower end of the reservoir where afterwards the sediment could be more cheaply disposed of by sluicing or dredging because of its nearness to the dam; (3) unfortunately, however, the topography alongside the San Carlos Reservoir site was so unfavorable that the canal, whether large or small, would be of prohibitive cost; and (4) even were the canal more promising than it then appeared, yet it would not be wise to load the irrigation project with its cost, for it could as well be built at some future date, when the advisability of doing it may seem more clear and when the lands to be benefited have, through cultivation and through redemption of a portion of their debt, become better able to bear the cost.

Perhaps the most notable example of a bypass canal in this country is connected with Lake Overholser, an impounding reservoir, constructed between 1916 and 1919, by Oklahoma City, Okla., on the North Canadian River (5) (fig. 27). About 8 miles west of this city the valley of the North Canadian River narrows to less than a quarter of a mile and is flanked by bluffs. Between these bluffs an Ambursen-type concrete spillway structure was constructed, 1,100 feet long and 39.5 feet in height above stream bed. This structure, supplemented by earth embankments on the flood plain, aggregating 2 miles long, created a reservoir that covered 1,700 acres and had an original capacity of 21,480 acre-feet.

About $2\frac{1}{2}$ miles above this dam, an embankment running across the valley, built some years previously for an electric interurban railway, was utilized as a diversion dam, as well as to create a desilting basin covering 800 acres and having a storage capacity of about 10,000 acre-feet. A bypass canal was constructed from this embankment along the side of the valley to the main spillway structure below by raising an earthen dike between the reservoir and valley side. This bypass channel had a bottom width of 120 feet, a depth of 20 feet, and a fall of 0.8 foot per 5,000 feet.

The original diversion gates in the railway embankment, and a set of gates in the upper end of the canal, used for releasing water into the reservoir, as well as the spillway and gates of the main dam, were all designed on the assumption that the maximum flood flow recorded prior to 1919, 5,200 second-feet, would not be greatly exceeded. The spillway and gates of the main dam, for example, were designed to pass 7,700 second-feet. In 1923, a peak flood discharge, estimated to have been 133,000 second-feet, caused severe damage to all control structures. Reconstruction of the reservoir began immediately after the flood, and cost \$1,400,000, or almost as much as the original cost of the development, which was \$1,500,000.

The old system of inlet gates at the upper end of the canal was abandoned, and a new Rollover diversion dam, 1,353 feet long between abutments, was built below the railway embankment and the site of the old inlet structure (fig. 27). The new structure is a reinforced concrete ogee weir equipped with four 25-foot stop-log sections and one 11.67-foot vertical gate. Flashboards can be used to raise the water level in the sedimentation basin an additional foot, but they are designed to give way in flood. Flow over the diversion dam is controlled by manipulating gates in the bypass canal. In flood, all water in excess of the capacity of the canal will automatically flow over the diversion structure and will be released through the main dam gates.

The main dam, as rebuilt, contains 30 large Tainter gates of various designs, and an open spillway section 125 feet wide. The maximum discharge capacity of the dam was increased to 225,000 second-feet. Four sluice gates were built into the spillway but have not been used, according to local reports.

The bypass channel is controlled by a 120-foot wide section at the east end of the main dam. In this section are four 9- by 14-foot flood-gates, which release water into a wasteway that enters the old river channel about 1,200 feet below the dam. The bypass canal has been protected against erosion by a gunite-reinforced slab covering. The main feed gates from the channel to the reservoir are in a reinforced

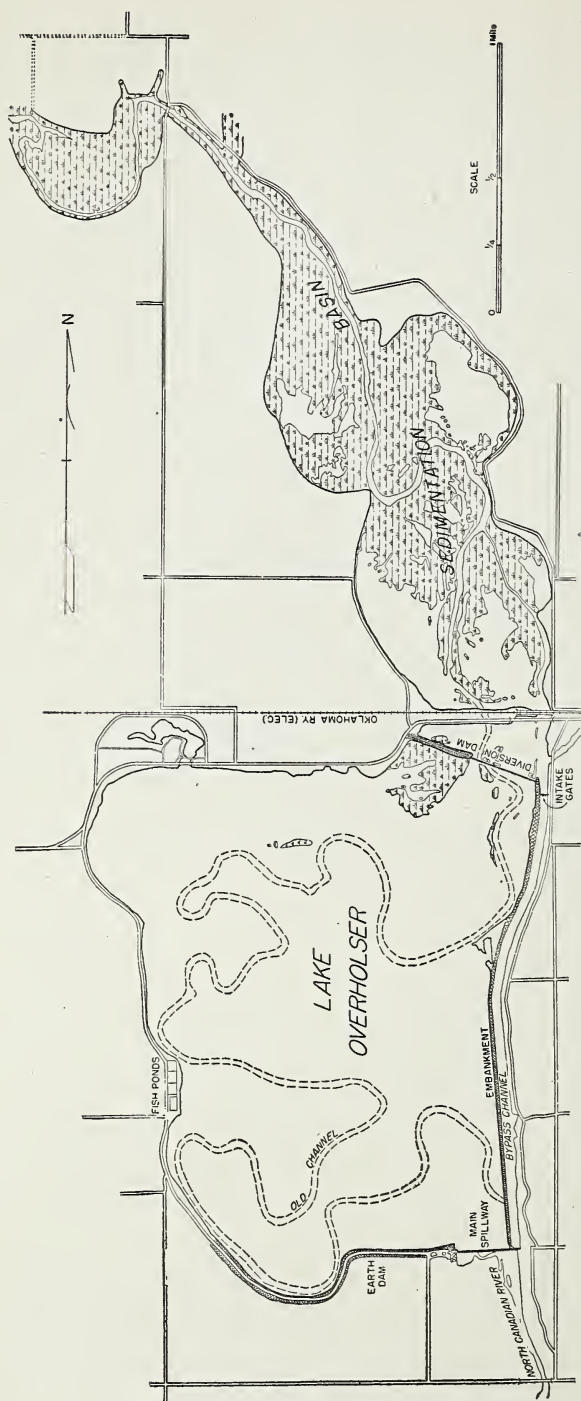


FIGURE 27.—Map of Lake Overholser, water-supply reservoir of Oklahoma City, Okla., showing bypass channel along east side of reservoir and sedimentation basin above it.

concrete structure 100 feet long, connected with, and at right angles to, the main dam, and forming the end of the bypass embankment. Four 4- by 6-foot gates in this structure regulate the supply to the reservoir.

In February 1942 a reconnaissance sedimentation survey of Lake Overholser, made by the Soil Conservation Service, revealed that approximately 3,262 acre-feet of sediment has been deposited, reducing the original capacity by 17.1 percent in 23 years (based on an estimated original capacity of 19,080 acre-feet—2,400 acre-feet less than determined from an original survey). Inspection of the sedimentation basin above the reservoir indicated that it had lost from two-thirds to three-quarters of its original capacity and had probably trapped 7,500 acre-feet of sediment, including above-crest deposits.

The average annual flow of the North Canadian River is about 200,000 acre-feet. Measurements of sediment removed from the city's settling basins in 1912 indicated a load of fine suspended sediment equivalent to 1.176 percent by volume in a year of less than average flow (4). If it were assumed that the average sediment load of the river was only 1 percent of the flow by volume, or 2,000 acre-feet annually, the reservoir and settling basin have trapped 23 percent of the load, and 77 percent has been carried through the canal; the bypass canal and settling basin combined have kept 93 percent of the sediment out of the main lake.

Campbell (38) has described a bypass canal and tunnel constructed as part of the present water-supply system of Durbin, Natal, Union of South Africa. The storage available in Camperdown Reservoir, the older supply of Durbin, was found by surveys to have been reduced from an original capacity of 1,854 acre-feet in 1902 to 862 acre-feet in 1918 and 552 acre-feet in 1926, a depletion amounting to 70 percent in 24 years. As a result of this loss and of increased water needs the Vernon Hooper Dam was constructed between 1923 and 1927 on the Umlaas River. The dam is a concrete gravity-type structure, 87 feet in height above river bed and 808 feet long. The storage capacity of the reservoir formed by this dam is 79,791 acre-feet. At the upstream end of the reservoir a flood-diversion weir 49 feet high was constructed on the river. Leading from it a canal, 20 feet wide, capable of carrying water 8 feet deep, or a flow of 1,200 second-feet, was excavated to a tunnel 1,200 feet long, which carries the flow through a mountain to a point below the dam. The tunnel itself will carry a flow of 8,000 second-feet and is connected not only with the canal but also with the reservoir. The opening of the tunnel, controlled by a 4- by 6-foot Stony sluice gate, is so located that when the gate is open the current in the upper part of the reservoir (below the diversion dam) flows directly to it, and to a large extent inflowing water passes through it and out of the reservoir. Thus only a small part of the water of flood flows or of their heavy sediment loads reaches the lower part of the reservoir basin.

Edgecombe (47, pp. 4-5), in discussing silting in Elephant Butte Reservoir, briefly described a proposal made by Follett for the construction of an 8-foot-diameter concrete tube laid on the river grade of 4 feet to the mile, from a point in the river bed near the upper end of Elephant Butte Reservoir to the dam, passing through the dam at about river grade. Such a tube was estimated to have a capacity of 300 second-feet. At the upper end of the tube a 10- or 15-foot overflow

dam was to be built. The storage area above this dam would form a settling basin that would be flushed out by drawing water through the tube. The entire low-water flow would pass directly through the tube, and not enter the main reservoir. The cost was estimated to be \$4,000,000.

A board of engineers, who considered Follett's scheme, came to the following conclusions, quoted in part:¹³

The reservoir as now planned will remain sufficiently capacious in spite of silting up for a long series of years. When its contents shall have become seriously diminished by silting, the dam can be readily raised to compensate for storage loss, for the time being at a cost far below that involved in constructing the work proposed by Mr. Follett. It can not be denied that there is a limit to this method of fighting the silt problem, but it is believed that engineering science in its continued progress will suggest economical methods for ultimately solving this problem. By that time also it is probable that values dependent upon the reservoir will have become greatly increased, and that at such future time expenditures may be incurred which may be regarded at present as excessive. Furthermore, accumulating interest on the investment if made for this purpose at the present time, would go far toward paying the cost of future remediable measures.

* * * the scheme must be regarded as an experiment on an enormous scale. Difference in opinion as to probable results will therefore exist among engineers. We fear that so long as the tube remains open it will be only partially effective in carrying silt through, and that there is great danger that with incoming floods the tube will become clogged with sand.

Hughes (*123, p. 150*) discussed the merits of a similar plan suggested for San Carlos Reservoir as a substitute for the high-level bypass canal. He listed the advantages of the conduit as follows: (1) The diversion dam, of about the same dimensions as required for the canal, would not be so far up the river by some 10 or 12 miles; for the conduit would not need to be longer than the reservoir whereas the canal would have to be well above spillway level because of topographic conditions and would therefore have to take off much farther upstream. (2) The conduit would carry the low-water flow of the river and a fraction of the flood waters, thus reducing the amount of sediment which otherwise would enter the reservoir. (3) In time of flood the conduit, taking its water from the bottom of the stream where the concentration of sediment is greatest, would convey as large a load of sediment as could be allowed, at the time, to reach the river bed below the storage dam. At other times the clearer conduit water would need to be fed en route or at the dam with additional sediment from the reservoir, and during much of the year stored water, too, would need to be added, either in the conduit or at the dam, to supply the needs of irrigation. (4) The conduit, fed from the river above, if made large enough and controlled at the dam, could supply more head for power purposes than the dam alone would furnish except when the reservoir was nearly full or the river above was low.

But in the application of this plan to the San Carlos Reservoir, Hughes considered the following drawbacks to be so great as to prohibit its adoption: (1) The conduit would be endangered by floods occurring when the reservoir was not full, for floods in the past have shifted the channel throughout the floor of the valley. (2) The conduit would be subject to pressures, internal and external, ranging from

¹³ Memorandum by a board of engineers consisting of W. L. Marshall, D. C. Henry, and L. C. Hill to the Director, United States Reclamation Service, dated December 5, 1913. Files of Bureau of Reclamation, United States Department of the Interior. [Unpublished.]

zero at the upper end to that due to a head of 180 feet of water, or nearly 80 pounds per square inch near the dam, and sooner or later either would occur without the other to counter-balance it, as in case of full reservoir and empty conduit, or empty reservoir and full conduit, with its outlet closed or choked. Hence, great strength would be required, which, in connection with the necessarily large size would make it very costly. (3) The conduit with waters heavy with sediment was liable to become choked like storm drains and dredge pipes, for it would not be practicable to regulate at all times the percentage of sediment entering it. Even with a small percentage of sediment, choking would not be unlikely at times when the outlet was closed, for in practice there would be leakage past the gate; inflowing water would escape but the sediment would be left in the conduit.

Reed (99) has described the diversion dam and bypass tunnel constructed above the Amsteg Reservoir, which was completed in 1922 in the Pfaffensprung gorge of the Reuss River, Switzerland, to provide power for the Swiss Federal Railways. The Amsteg Dam is a ma-

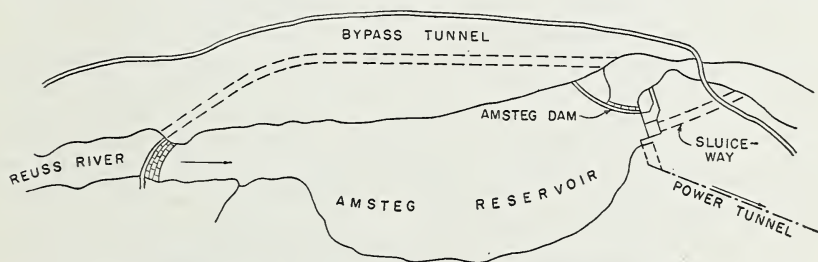


FIGURE 28.—Sketch map of Amsteg Reservoir on the Reuss River, Switzerland, showing bypass tunnel. (After Reed.)

sonry arch structure 105 feet high, but with a storage capacity behind it of only 160 acre-feet. The drainage area above the reservoir is 156 square miles, and the flow of the Reuss River ranges from a minimum of 70 second-feet to a flood flow of 14,000 second-feet. In order to prevent river debris from filling the reservoir, a bypass tunnel was constructed around the reservoir as shown in figure 28. This tunnel is 1,000 feet long and has a cross-sectional area of 225 square feet and a flow capacity of 7,800 second-feet. Flow is diverted into the tunnel by a cyclopean masonry weir at the head of the reservoir. The flow through the tunnel is regulated by two motor-operated inlet gates, each 17.7 feet wide, so that the flow into the pond is only sufficient to supply the power-plant demand. During the low-water season, when the full flow is utilized through the plant, little sediment is carried by the stream. During flood periods about one-third of the total flow is spilled over the diversion dam and passes through the pond. This, however, is that part of the stream flow near the surface, which carries only silt and fine sand, while the larger part of the flow heavy with debris is bypassed through the tunnel. Observations made after three years of operation showed that deposition in the pond had been insignificant.

Appraisal.—Probably a fair appraisal of diversion channels, or closed conduits on the bottom of a reservoir, is Schoklitsch's statement

(107, p. 66) that "such arrangements can be considered providing the reservoir is short and the locality permits construction of such a device at legitimate expense." The question of what may be considered legitimate expense involves the economics of the particular project. With the exception of the diversion channels around Oklahoma City's Lake Overholser and Durban's Vernon Hooper Dam, the known examples of use of bypassing channels have been in connection with power dams that created pondage only. The exclusion of sediment at power dams has been primarily to prevent filling of the small regulating pool necessary to maintain constant head, or to reduce sediment damage to turbines and other power equipment.

The construction of a canal around a reservoir that has many indentations or embayments would be very expensive. In some places basin-type reservoirs are so situated that the head of backwater is close to the dam and a short canal or tunnel would permit diversion of flood flows to a point below the dam. In other places a tunnel might permit diversion to an adjacent drainage basin. Conduits on the floor of a reservoir have never been tried, largely because of their great cost and other objections brought out in this section.

Water requirements and other factors that must be considered in diversion practice with off-channel reservoirs also affect the use of bypass channels or conduits. In fact, no essential difference exists between off-channel reservoirs and these types of diversion except that in the former scheme storage water is led to the reservoir and in the latter schemes flood flows of sediment-laden water are led around the reservoir, or under it.

CONTROL OF SEDIMENT DEPOSITION

The deposition of sediment in a reservoir can be controlled to a certain extent by designing and operating gates or other outlets in the dam in such a manner as to permit selective withdrawal of water having a higher than average sediment content. The suspended-sediment content of part or all of the water in reservoirs is higher during and just after flood flows. Thus, the more water wasted at such times the smaller will be the percentage of the total sediment load to settle into permanent deposits. Furthermore, water at various levels in a storage basin often contains radically different concentrations of suspended sediment, particularly during and after flood flows. Hence, if all waste water could be withdrawn at those levels where the concentration is highest, a significant amount of sediment might be vented from the reservoir.

The most effective control of sediment deposition can be obtained by building into a dam outlet works that permit the greatest selective control of water release. Even with the control works available at many existing dams, although poorly designed from this standpoint, a revision of operating practices would undoubtedly result in the prevention of deposition of considerable quantities of sediment that, under present practices, are settling to the reservoir floor.

VENTING DENSITY CURRENTS

It has been known for several decades that water in natural lakes or impounding reservoirs may be stratified or layered, with some layers having higher or lower temperatures than others, greater or less

salinity, greater or less suspended sediment, or other differences. Differences in temperature, salinity, hydrostatic pressure, and sediment content cause differences in the density of the various layers of water.

A density current has been defined as a gravity flow of a fluid under, over, or through a fluid of approximately equal density. Density currents have been referred to also as stratified flows, density flows, underflows, and tunneling of silty water. These currents and their effect on reservoir silting have been described recently by Bell (21).

Insofar as reservoir silting is concerned, the only density currents of importance are those that transport sediment from upper and higher parts of the lake to its low reaches, especially to the dam. In the following discussion it is assumed that the density differences causing these flows result primarily from suspended sediment, and that the effects of temperature, salinity, and other factors are subordinate. Existing data are for the most part insufficient to indicate the importance, quantitatively, of these several factors in the development and maintenance of flows of silty water.

When a relatively muddy stream enters a clear reservoir, the inflowing water collides with the "still" water of the lake and partially mixes with it. If the mixture is heavier than the reservoir water it sinks, often appearing to plunge beneath the surface (fig. 29, A), until it encounters water of equal density or, if such water is not present, until it reaches the bottom of the lake. At the point of sinking the inflowing current often meets an upstream current, which has been generated by the movement of water along the surface to replace the water carried down the lake as a result of mixing with the muddy river water. An accumulation of driftwood may mark this point of junction (fig. 29, B).

As all impounding reservoirs have a bottom slope, gravity causes the turbid inflowing current, when it is denser than the impounded water, to move along the bottom of the reservoir toward its lowest point (fig. 30). If the turbid inflow is less dense than colder or more saline impounded water, the flow may move along the reservoir surface or between more dense and less dense layers within the lake. Underflows, overflows, and interflows have all been recorded in Lake Mead. Coarse particles of sediment tend to settle out continuously, but fine particles may be entrained by a density current moving along the bottom. A sediment-laden flow may be dissipated, as such, before reaching the dam; or the current may persist after all sediment has settled out, because of temperature or salinity differences. Some observations on Lake Mead have suggested, however, that the flow had a higher sediment content at the dam than farther upstream.

When an underflow hits the dam, it tends to rise against this solid barrier; and if the lake is shallow, it may come to the surface and part of it may flow over the spillway. Generally, however, it settles back to form a submerged lake of static muddy water from which particles of sediment settle slowly over a period of days or weeks.

Measurements in Lake Mead indicate that the muddy lake there does not have a horizontal surface, but slopes toward the dam on a gradient of about 1 foot per mile.

Density currents probably seldom attain an average velocity of more than 1 mile per hour in passing through a reservoir. The mean velocity in Lake Mead, where the phenomenon has been most studied,

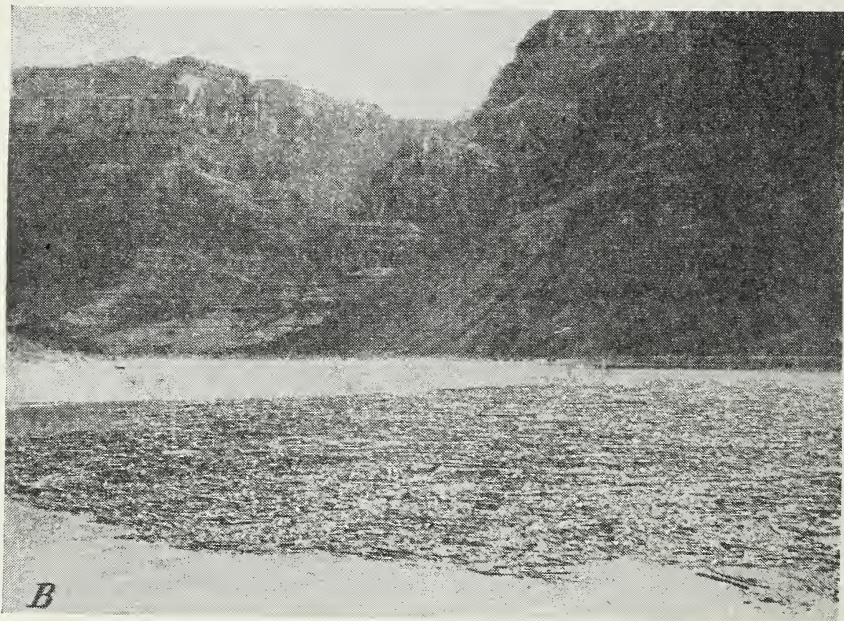


FIGURE 29.—*A*, Flow of muddy water coming into Lake Mead, on the Colorado River. At this point the flow begins to sink beneath the clear water already in storage. *B*, Accumulation of driftwood where upstream surface current meets inflowing current. (Photos by U. S. Bureau of Reclamation.)

is about 0.6 mile per hour, although in canyon sections of this reservoir maximum velocities of as much as 2 miles per hour have been measured. Observations at Elephant Butte Reservoir on the Rio Grande, where density currents have passed through the lake when it was 30 to 35 miles long, indicated rates of 0.25 to 0.75 mile per hour (52). A

muddy density current passed through Echo Reservoir on the Weber River, Utah, August 6, 1934, with a speed of 0.13 mile per hour (64, p. 772), and currents through Lake Arthur Reservoir in South Africa are reported to have traveled at a rate less than 0.34 mile per hour (64, p. 757). Johnson (74) estimated a velocity of 0.068 mile per hour, or less, for a flow through Lake Issaqueena, near Clemson, S. C.

Density currents may persist on very low slopes. Interflows between submerged, muddy lake water below and clear water above have moved 30 miles through Lake Mead on slopes no greater than 1 foot per mile.

The most reliable information now available indicates that density currents may develop and persist with very low concentrations of fine sediment (less than 20 microns).

Grover and Howard's data (64) show that during the periods when density currents passed through the Lake Mead outlet tunnels, which were permanently sealed May 1, 1936, the concentration of sediment in the outflows ranged from 0.31 to 1.76 percent by weight. In fact,

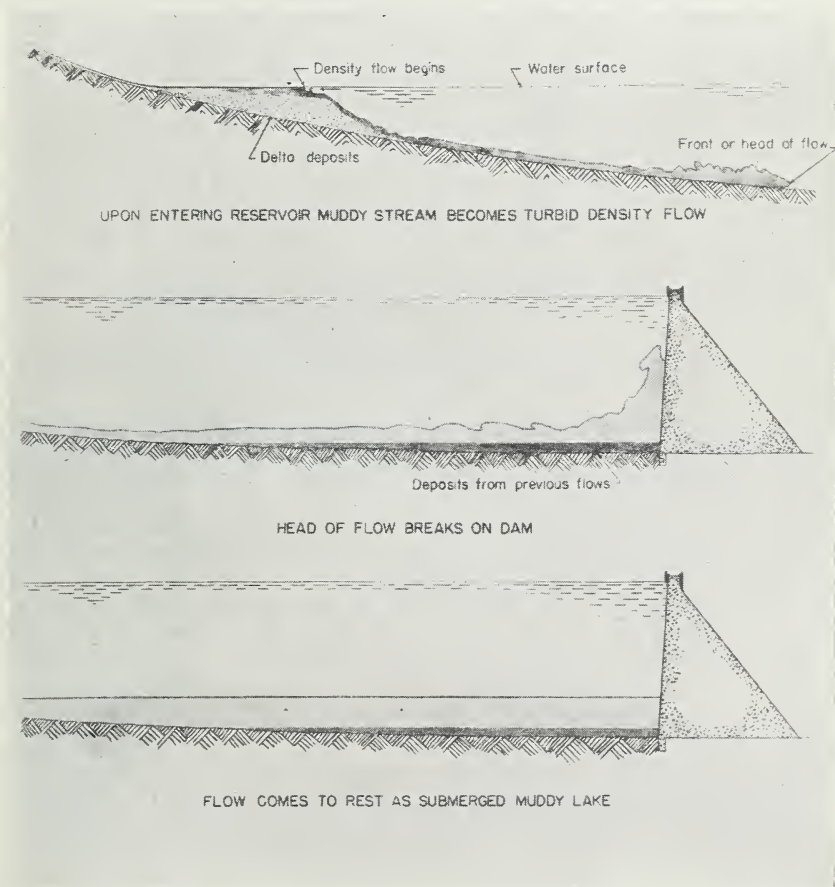


FIGURE 30.—Life history of a density flow. (After Bell.)

lower concentrations, 0.08 to 0.12 percent by weight, in outflows during the first month of impoundment, February 1935, may have been the result of density currents. Bell (21), on the basis of admittedly meager evidence, interprets the density-current measurements in Lake Mead to indicate that sediment concentrations in active underflows in that lake are rarely in excess of 8 or 9 percent by weight.

Lawson (82) reported sediment concentrations of 1 to 7 percent by weight in the density-current outflow from Elephant Butte Reservoir during July 1919. Bliss (64, p. 749) gave figures on concentration ranging from 1.55 percent, or less, to 7.80 percent by weight for Elephant Butte density flows in 1931, 1933, and 1935. Fiock (52) stated that the concentration in flows through this reservoir ranged from 2 to 6 percent by weight.

Some critics of Grover and Howard's paper (64) were of the opinion that density currents did not persist through a lake, or at least through Lake Mead, unless the inflowing water contained a concentration of more than 2 percent by weight of sediment. Evidence now available indicates, however, that well-defined density currents, containing very low sediment concentrations, may move completely through long reservoirs. Wiebe (134) reported a density current in Norris Reservoir, Tenn., on August 5, 1938, that contained only 0.03 to 0.05 percent of sediment by weight. Armstrong¹⁴ has recorded data from Loch Raven Reservoir, water supply for Baltimore, Md., that indicate the occurrence of a density current on November 5, 1932, with turbidities ranging from 73 to 120 p. p. m. Density current studies in Lake Issaquena, described by Johnson (74), have shown that such flows occur with a sediment concentration of only 0.01 percent (fig. 31).

The thickness of muddy density currents may range from a few inches up to, perhaps, 100 feet or more. Usually the interfaces or boundaries of density currents are sharp, and differences in concentration on either side of the interface are great. In some occurrences, however, a rather thick transitional zone of decreasing turbidity between the main stratum of the density current and the overlying or underlying clear water has been reported.

According to Fiock (52), density currents moving along the bottom of Elephant Butte Reservoir were found to be less than 5 feet thick. Other observers have reported flows in this reservoir less than 1 foot thick. Page (64, p. 745) stated that density currents that passed through the outlet tunnels of Lake Mead in February 1935 were about 2 feet thick in their center. Lewis (64, p. 757) reported that the thickness of the flow of concentrated sediment along the bottom of Lake Arthur was seldom greater than 3 feet. Wiebe's diagrams indicate a thickness of about 10 feet for density-current interflows between layers of clear water in Norris Reservoir (fig. 32). Measurements in Lake Mead subsequent to closing of the outlet tunnels indicate thicknesses of more than 100 feet.¹⁵

An overflow of muddy water in the lake formed by Wilson Dam at Muscle Shoals on the Tennessee River, Ala., is reported to have

¹⁴ ARMSTRONG, J. W. LOSS OF STORAGE CAPACITY IN THE LOCH RAVEN RESERVOIR DUE TO SILTING. Bur. Water Supply, Baltimore, Md., Request No. 28, 7 pp., illus. 1933. [Unpublished.]

¹⁵ NATIONAL RESEARCH COUNCIL, SUBCOMMITTEE ON LAKE MEAD INTERDIVISIONAL COMMITTEE ON DENSITY CURRENTS. LAKE MEAD DENSITY CURRENTS INVESTIGATIONS, 1937-1940. 2 v., illus. Denver, 1941. [Processed.]

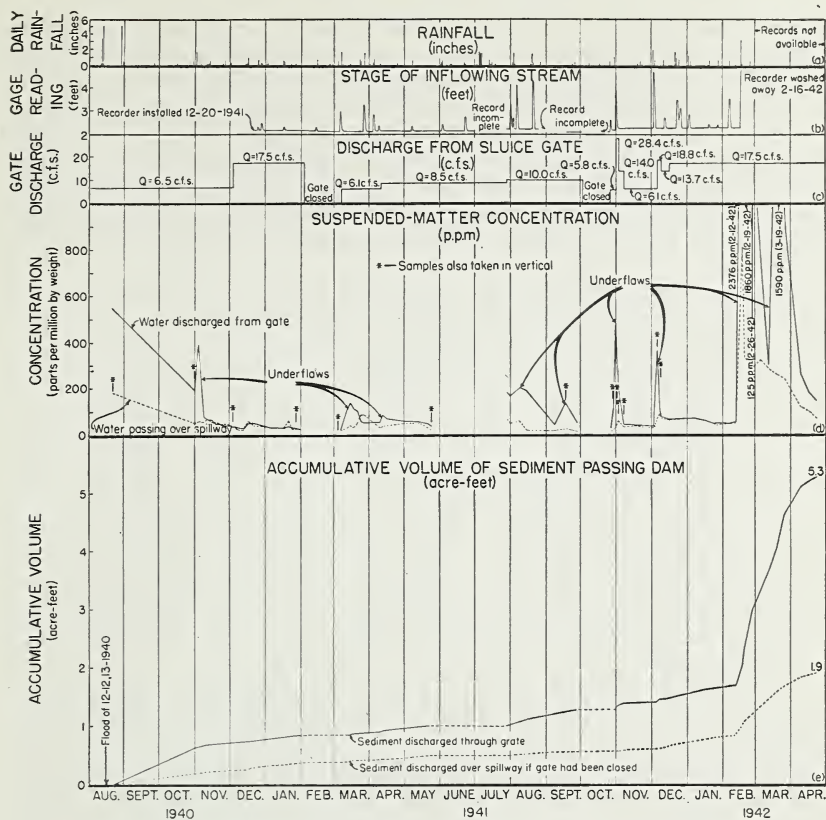


FIGURE 31.—Results of study of density currents in Lake Issaqueena, near Clemson, S. C.

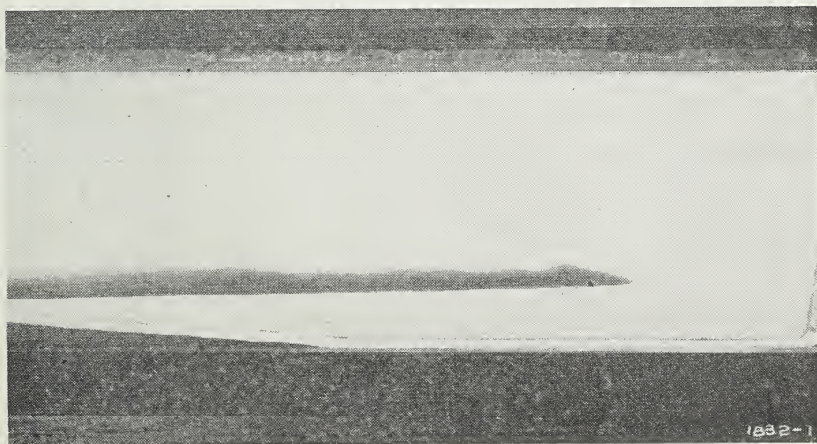


FIGURE 32.—Interflow of silty water in laboratory tank. From experiments at Cooperative Laboratory of Soil Conservation Service and California Institute of Technology, Pasadena, Calif.

been 27 feet thick.¹⁶ Below this was a zone of clear water while at the bottom of the reservoir there was a muddy layer 2 feet thick moving as an underflow. An interflow of muddy water at Lake Murray, on the Saluda River in South Carolina, was observed in December 1931 by the reservoir operators, who reported that turbidity was encountered 25 feet below the surface and increased to a depth of 80 feet where it reached a maximum.¹⁶ Below this depth the turbidity decreased until clear water was again encountered at an unrecorded depth. The total depth of water at the point of observation was 170 feet.

Sediment-laden density currents nearly always have other characteristics that distinguish the water in these layers from bounding water strata. Measurable differences in temperature, dissolved oxygen, hydrogen-ion concentration, dissolved salts, and electrical conductivity have been reported. Fiock (52) noted that muddy outflows from Elephant Butte Reservoir had temperatures 6° F. higher than the overlying lake water. Outflows from Lake Mead in 1935 were 11° F. higher than overlying lake water (64). Higher temperature, of course, tends to make the water less dense and, hence, to offset the effect of sediment, which must thus be present in greater concentration than otherwise to cause the formation and maintenance of the density flow. Density currents, however, are just as likely to be colder than the stored water. Wiebe (134) and Ellis (48) have discussed the various properties of water that are associated with density currents.

The quantities of sediment transported by density currents is of great practical importance. Grover and Howard (64) reported that during 3 periods in 1935 density currents passing through Lake Mead carried out of the lake 6,000,000 tons of sediment, or about 2.5 percent of the estimated average annual load of sediment brought into the lake. Fiock (52) reported that up to 1935 about 5,000 acre-feet of sediment had been vented from Elephant Butte Reservoir, or approximately 1.4 percent of the accumulation in the reservoir to that date. From the results of density-current observations in Lake Mead, Bell (21) estimated that about 232,000,000 tons of solid matter was brought into the lower part of the lake by these currents between the date of closing of the tunnel outlets, May 1, 1936, and May 20, 1941. This is close to one-third of the total sediment load brought into the lake during this period. As this sediment was all transported by density currents and is now confined to a submerged muddy lake that extends only 35 miles above Boulder Dam, it might be reasonably assumed that had suitable outlets been installed in this dam and had it been possible to operate them with a view to releasing this sediment, probably 75 to 90 percent of it could have been passed through the dam. According to Bell, if it were assumed (1) that Lake Mead would be completely filled with sediment in 200 years, and (2) that the average final compaction of sediment would reach a value of 60 pounds per cubic foot, then venting this percentage of the underflows could have increased the useful life of the lake 35 or 40 years. The reader should not assume, however, that such a procedure necessarily would have been advisable, for one of the func-

¹⁶ Minutes of meetings of the Interdivisional Committee on Density Currents, National Research Council, on June 14 and 15, 1937. [Processed.]

tions of Lake Mead is to store sediment and prevent it from doing damage downstream.

Studies of density currents in Lake Issaqueena, located on Six Mile Creek near Clemson, S. C., have been made by the Soil Conservation Service since August 1940. This reservoir was completed in June 1938 for recreational purposes by a gravity concrete dam 51.5 feet in height above bedrock. The original capacity of the lake was 1,836 acre-feet and its drainage area was approximately 14 square miles. A sedimentation survey made in April 1941 showed that the capacity had been reduced 4.79 percent by the deposition of 88 acre-feet of sediment.

Figure 31 shows the results of measurements made from August 1940 through April 23, 1942. During this period one of the two outlets near the base of the dam, a 30-inch gate that controls the flow into a 24-inch pipe, was opened sufficiently to allow from 5.8 to 28.4 second-feet of discharge. Just after a heavy flood in August 1940, the suspended-matter concentration in flow coming from the outlet pipe was 552 p. p. m., while that passing over the spillway was 183 p. p. m. Following each of 9 periods of storm runoff between November 1940 and April 1942, the peak concentration in the gate discharge occurred earlier than the peak concentration passing over the spillway.

The curves of figure 31, *e*, show the sediment discharged through the gates and the probable loss that would have occurred over the spillway if the gates had been continuously closed. In other words, opening one of the two gates in the dam to an average of less than one-tenth of their combined rated capacity (approximately 230 second-feet with full head) more than doubled the sediment loss from the lake, and decreased sedimentation during the entire 20 months of record by more than 3.4 acre-feet. Although this is a relatively small amount, it seems clear from the observations that if the gates had been opened according to a prearranged plan governed by forecasting flood flows in the drainage area, at least 10 percent of the incoming sediment, and possibly as much as 25 percent, could have been vented through the two outlets, without adversely affecting water storage in the lake.

A series of laboratory studies by R. T. Knapp and H. S. Bell at the Cooperative Laboratory of the Soil Conservation Service and California Institute of Technology, Pasadena, Calif. (21), has shown (1) that density currents may occur as underflows, interflows, or overflows, depending upon the relative densities of the fluid masses involved, (2) that a density current will form and persist in laboratory flumes with very small concentration of sediment, and no difference in other physical characteristics, and (3) that density currents can be withdrawn through openings in the dam.

Because a submerged outlet draws water toward it from all directions, the vertical dimension of the opening must be small with respect to the thickness of the layer from which water is to be withdrawn, or the rate of withdrawal must be very slow. Otherwise, water may be pulled in from layers above and below, as well as from the layer that it is desired to vent. Considering the known dimensions of muddy underflows, large openings are probably not so desirable as a greater number of smaller openings. The data now available are not sufficient for formulating any general rules on the number, spacing, and distri-

bution of outlets and control works required for most effective venting of density currents. The plans will necessarily vary for every set of conditions, and further research in both fundamentals of the phenomenon and in design is needed to establish general principles.

An alternative method of venting underflows, although only tried on a model scale, consists of placing a curtain or screen in front of the dam. Such a metal or thin concrete curtain in front of the dam would force wastage of the sediment-laden water at the bottom of the reservoir rather than of the water at the surface (fig. 33).

Appraisal.—The occurrence of sediment-laden density currents as underflows, interflows, or overflows, under widely differing conditions, has been reported at more than two dozen reservoirs scattered throughout the United States. This leads to the conclusion that these currents may be expected to occur anywhere, if certain combinations of conditions exist. Unfortunately little quantitative data have as yet been obtained on the characteristics of the phenomenon, and even less on its potentialities as a method of reservoir-silting control. Obviously, the questions of practical importance are: (1) What percentage of the sediment brought into a reservoir will be carried to the dam by density currents, and (2) what kinds of outlet works would be most effective in venting these currents.

The present lack of information and the important potentialities of density currents make it especially desirable to obtain further observational data of existing lakes. Reservoir owners and operators should seriously consider establishing one or more stations in the reservoir at which regular measurements will be made over a period of several years. At least one station should be located just above the dam, and preferably two or more additional stations should be located at points up the lake, one just below the inlet or delta, and one in the middle section. Such stations might consist of permanently anchored rafts from which measurements could be made of the temperature and conductivity gradient from the surface of the lake to the bottom and water samples collected at various depths for determination of sediment content or turbidity.¹⁷

Rough indications of sediment content have been obtained by an automatic turbidity-recording device described by Ellis (48). While this equipment probably would be satisfactory in connection with an operating plan of venting underflows, it gives data less valuable for preliminary experimental purposes.

Regular observations should be made at least once a week, but if arrangements can be made for reporting storm runoff from the drainage basin, and if frequent observations are recorded during and immediately after this runoff, observations during intervening periods might be made at intervals of several weeks.

With the information now available it seems entirely reasonable to expect that 10 to 20 percent and perhaps more of the incoming sediment might be passed through many reservoirs by venting density currents to the fullest extent possible through properly designed and controlled gates. Stevens comments (64, p. 769) that "although the total quantity discharged with only 2.5 percent of that coming into

¹⁷ Equipment for temperature and conductivity measurements has been described by Ellis (48). The Foerst water sampler, used by the United States Bureau of Reclamation in its observations in Lake Mead, has proved satisfactory for obtaining water samples. For a description of taking samples and making measurements, see work cited in footnote 15, p. 70.

Lake Mead in 1935, the fact that any at all was discharged is too important not to be investigated further." (Note that the sediment discharged was actually about 4 percent of the 1935 sediment inflow, but only 2.5 percent of the annual inflow.)

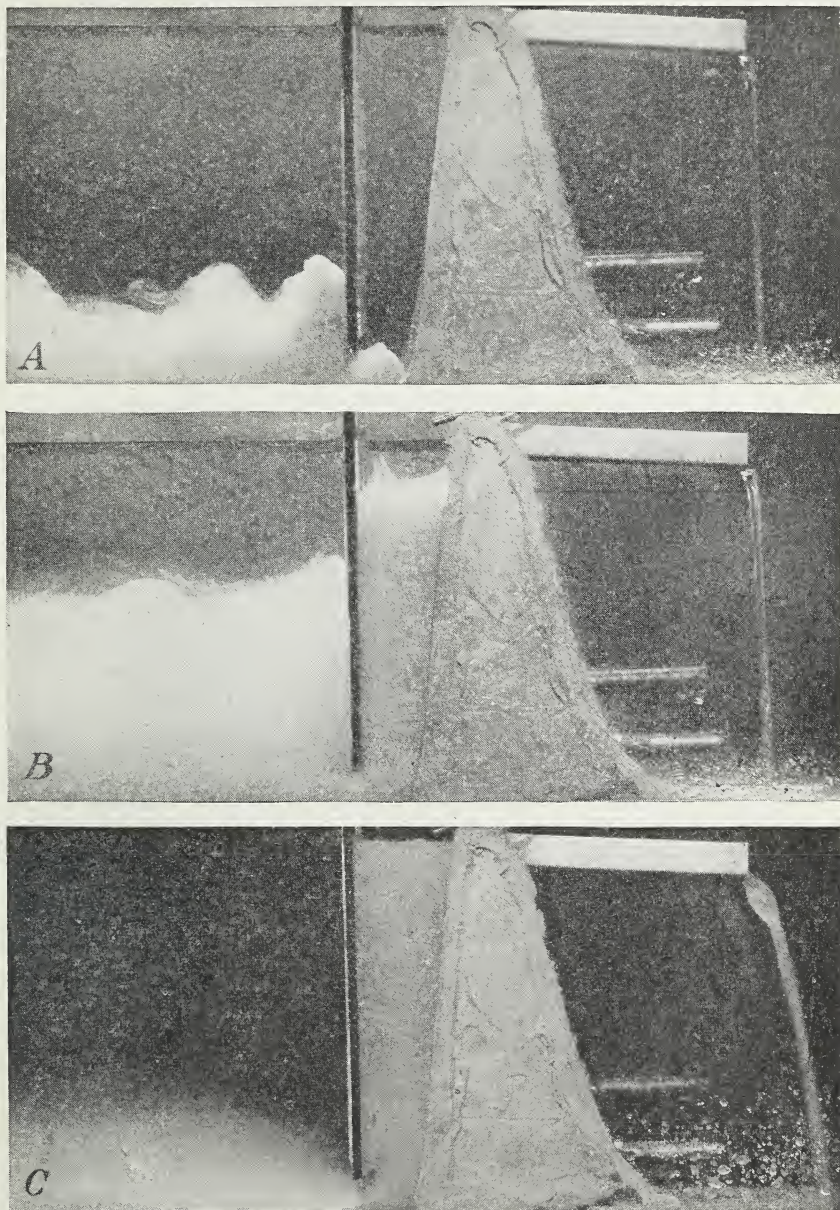


FIGURE 33.—Laboratory experiment showing effect of curtain in front of dam, forcing density current to flow over spillway: *A*, flow has just reached curtain; *B*, flow is rising between curtain and dam; *C*, flow is passing over spillway. (After Bell).

It must be recognized that some undesirable loss of water might result from the maximum possible release of density currents. In all reservoirs that lose water over the spillway during an appreciable part of the time, the release of water at levels where the maximum sediment concentration occurs would be a most desirable practice. In those western reservoirs that seldom spill, and where every acre-foot of water is believed to be indispensable, venting of density currents probably would be tolerated only when the water could be used below for irrigation. If, however, some wastage could be afforded, the remaining water of improved quality would probably be more productive per acre-foot than the average water of the whole reservoir.

Releases of turbid water would not necessarily have to be made at the time the density flow took place. If conditions similar to those found in Lake Mead exist, very muddy water would accumulate in the lower end of the lake and would retain its fluidity for days or weeks. It might be released at such times during this period as would best suit water requirements below the dam.

CONTROL OF WASTE-WATER RELEASE

When the storage capacity of a reservoir is much less than the normal annual runoff from the drainage area, water must be wasted past the dam from time to time. If the maximum wasting could be accomplished at those times when the water contained the greatest concentration of suspended sediment, the rate of silting of the reservoir would be reduced. Some types of reservoirs have, or can be equipped with, spillways or sluice gates that may be used advantageously to increase the amount of sediment passed through the reservoir.

Increased sediment wastage often can be obtained in dams designed with a center overflow type of spillway, equipped with tall Stoney, Tainter, or vertical lift gates. For any total height of dam, the greater the height of the gates and the less the height of the permanent spillway sill above stream bed, the greater will be the potential sediment wastage. The gate discharge capacity preferably should exceed, or be as close as possible to, the maximum stream discharge, and the whole spillway structure preferably should be located at right angles to the main force of the flood current.

It has long been known that the greatest concentration of suspended sediment is carried during the early stages of a flood. Bed load, on the other hand, is transported at a rate more or less directly related to discharge. This is illustrated by a typical hydrograph of flow and concentration of both suspended and bed sediment during a minor flood on the Enoree River near Greenville, S. C. (fig. 34). If a reservoir equipped with large gates had been located on this stream, and the entire flow prior to 2 p. m., August 18, 1939, had been passed, 62 percent of the water could have been held back, but only 40 percent of the suspended sediment load would have been trapped. An adequate system for forecasting the flood flow before it reaches the reservoir would be necessary, of course, for the proper timing of gate operations.

Kanthack (78 pp. 218-221), in discussing the control of sedimentation in reservoirs built for irrigation, power, and flood regulation in South Africa, concluded that where large withdrawals of water are made from these reservoirs, or when the reservoirs have a low ratio of capacity to inflow, spillways should be equipped with tall gates, ex-

tending down approximately 20 to 25 feet from the maximum required storage level. In most reservoirs of moderate size in South Africa, the greater part of the storage capacity is in the top 20 feet of the reservoir, a condition that is also true for many reservoirs in the United States. Kanthack pointed out that if eventually the basin fills with sediment to the permanent sill level at the bottom of gates 20 feet tall, no material loss of storage will have resulted. If surplus

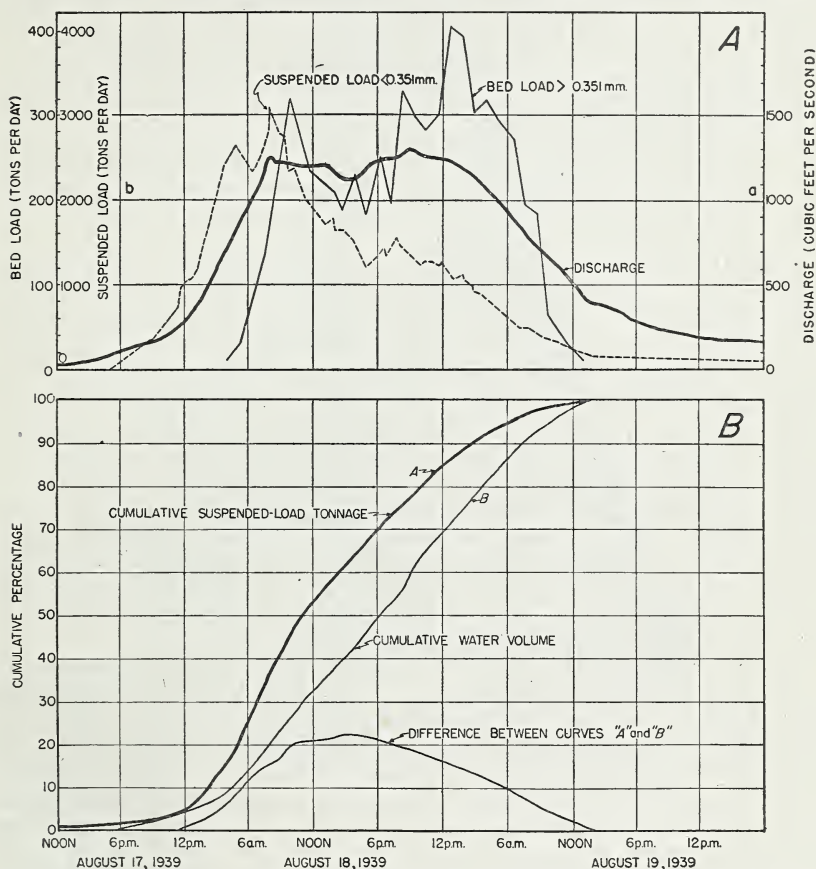


FIGURE 34.—Results of study of sediment transportation during a flood flow at the Enoree River Sediment Load Laboratory of the Soil Conservation Service near Greenville, S. C.: A, variation of suspended load and bed load, with discharge; B, relation of cumulative suspended-load tonnage and discharge.

water must be discharged from a reservoir, the opening for even a short time of a 25- by 30-foot spillway gate, in his opinion, would produce not only a very great scouring effect on any existing deposits but would also create a current that would keep finer sediment in suspension throughout the reservoir.

The Vaal River dam, 25 miles south of Vereeniging, Union of South Africa (6), consists of a series of 35 concrete piers, each 34.5 feet high and 8 feet thick with openings 30 feet wide between them. In the 36 openings between piers are 26-ton gates, 25 feet high and 32.5 feet wide,

operating between vertical roller trains in 18-inch slots in the piers. The gates are balanced by 60-ton counterweights and may be raised in $1\frac{1}{2}$ minutes. When the gates are closed a storage of more than 50,000 acre-feet is obtained within the channel. At the time of construction the channel was widened at the dam from 620 feet to 1,400 feet, so that the clear width of channel controlled by gates is 40 percent greater than average channel width. This assures a strong current of great scouring capacity through the dam. The flow of the Vaal River ranges from zero to 187,000 second-feet and the annual amount of sediment carried through the dam is estimated to be 1,200,000 tons.

In constructing reservoirs on sediment-laden streams in India, the objectives, according to Edgecomb (*47, p. 21*) are: (1) To select a dam site that will give large storage capacity with a relatively low dam, (2) to design an overflow spillway along the whole length of the dam, and (3) to equip the spillway weir with steel shutters on top from 6 to 8 feet high, so as to have the largest possible percentage of the total storage controlled by gates.

Instead of large spillway gates on top of a permanent weir, sluice gates large enough to pass maximum flood flows may be placed in the dam structure. The first great dam to be constructed with controllable sluice gates of sufficient size to pass large flood flows was probably the original Bhatgarh Dam, which created Lake Whiting on the Yelwandi River, about 40 miles south of Poona, Bombay presidency, India (*36, pp. 75-85*). This dam has now been superseded by the newer, higher Lloyd Dam just downstream, which was completed in 1928. All the information given here refers, however, to the older dam. The Bhatgarh Dam, built of concrete rubble and masonry, was completed in 1892 to a maximum height of 127 feet, or 103 feet above the river bed. Its length was 3,020 feet. The original storage capacity of the reservoir was 121,970 acre-feet. On each end of the dam were overflow waste weirs that contained 103 openings, 88 of which were fitted with 8- by 10-foot automatic gates.

The 15 undersluices, each 8 feet high by 4 feet wide and spaced 17 feet apart, were the significant feature in sedimentation control (figs. 35 and 36). The sills of these arched undersluices, which were centered over the main stream channel, were only 12 feet above the river bed. The undersluices were lined with cut stone and were closed by 2-ton iron gates, which slid vertically and were controlled by steel screws from the top of the dam. Screens of horizontal rails 1 foot apart were placed in front of the sluices to keep them from becoming clogged with timber and brush. Five other undersluices existed at higher levels. Schuyler (*108, p. 268*) gives the total discharge capacity of all undersluices as 20,000 second-feet, which compares with a maximum design flood discharge of 51,600 second-feet.

The drainage basin of 128 square miles has an annual precipitation ranging from 40 inches at the dam to 250 inches in the headwaters. Nearly all the rain falls during the monsoon season, and the first heavy floods come in July. In operating practice the sluices were kept open, normally under heads of 8, 15, or sometimes up to 30 feet, until seven-eighths of the average year's runoff had passed through the reservoir. The gates were closed about July 31, and the remainder of the runoff, equal to the reservoir's capacity, was stored. Much the greater part of the annual sediment load was carried

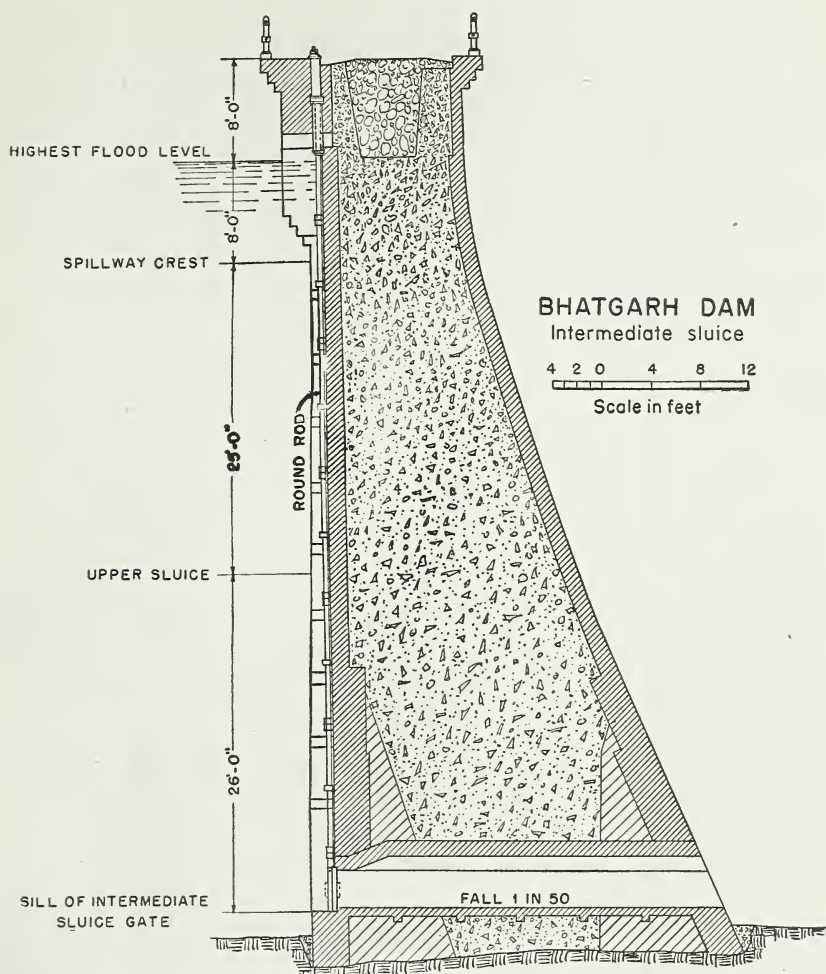


FIGURE 35.—Cross section of Bhatgarh Dam, India, showing undersluice. (After Buckley.)

through the reservoir, not only because seven-eighths of the water was wasted but also because the first flows of the season carried much higher concentrations (up to 1 percent or more) of suspended matter.

A head of 15 feet on the undersluices caused ponding for a distance of 3 miles above the dam. Consequently, some sediment was deposited in the reservoir, even when the undersluices were opened to pass the early floods. The surface of backwater, when the undersluices were open, was less than one-thirtieth of the area of the reservoir when full, so that twenty-nine thirtieths of the reservoir's bed was not subject to sediment deposition. In 12 years (1892-1904), according to Buckley (36, p. 87), Lake Whiting showed no signs of silting except for a few hundred yards upstream from the sluices. The quantity deposited above the sill of the undersluices in this period

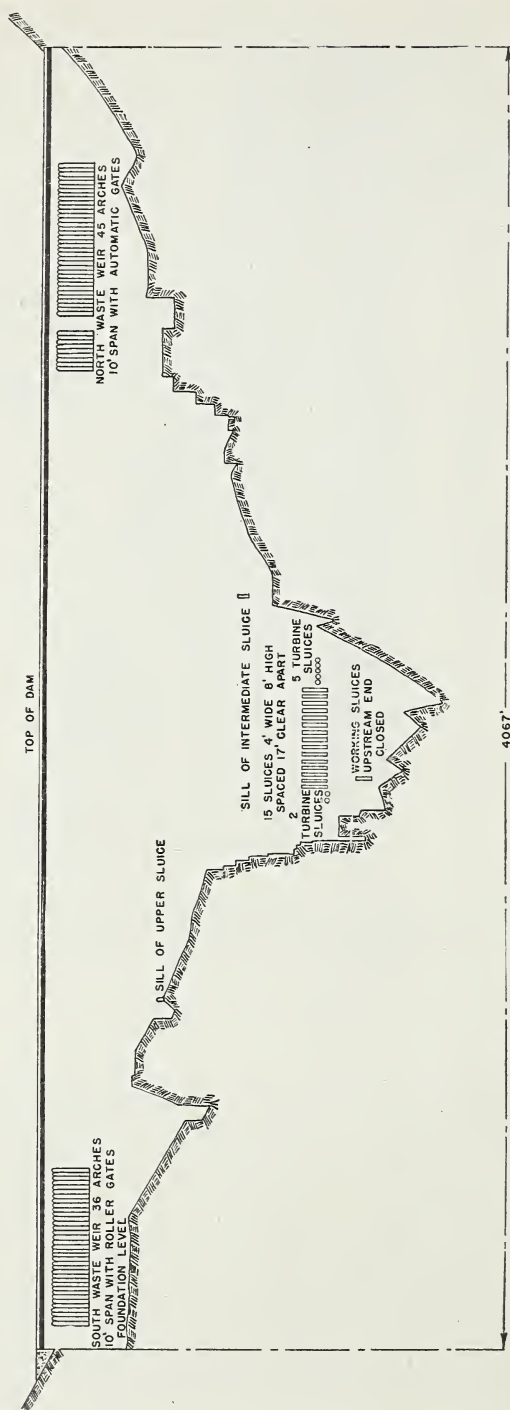


FIGURE 36.—Longitudinal section of Bhatgarh Dam, India, showing arrangement of sluice gates and undersluices. Downstream face. (After Buckley.)

was 86 acre-feet. Meyers (89) reported that at the time of his visit in 1910, the capacity was still practically undiminished.

The new Lloyd Dam, the crest of which is 60 feet above that of the old Bhatgarh Dam, maintains the same principle of sluicing. The lowest sluices in the new dam are 143 feet below maximum water level.

Lake Fife, of comparable size in an adjacent drainage basin, was not provided with undersluices, and lost 18 percent of its effective capacity from 1883 to 1905.

In general, the Indian practice is to provide sluices capable of discharging from one-third to the entire maximum daily discharge of the average year. This is about one-sixth of a flood of 20- or 30-year frequency. In other terms, the sluices should be sufficient to discharge the flow of a bank-full stage on the inflowing stream under a head of 5 to 10 feet at the sluices. Naturally, provision must be made to prevent scour from such a discharge below the dam.

The principle of allowing the sediment-laden water of floods to pass through the reservoir basin without appreciable diminution of velocity was applied in the construction of the famous Aswan Dam located on the Nile near Halfa, Egypt. This was the first insubmergible dam built without any provision for overflow waste weirs. The whole river discharge can be passed at all times of the year through sluices piercing the body of the dam. At Aswan the flow comes from a drainage area of 620,000 square miles, which yields an average annual runoff of about 66,000,000 acre-feet.

Torrential rain falls in the upper drainage basin during a monsoon period that begins about June 15. By the end of July and until January the Blue Nile and the Atbara are in flood, and transport vast quantities of sediment out of the Abyssinian Plateau where they head. From January to about the end of July the suspended load of the Nile, whose water at this period comes almost entirely from the White Nile, is less than 0.01 percent by weight. Toward the end of July, or during the first part of August, the sediment concentration increases rapidly to a maximum, which is usually reached late in August and precedes the arrival of the flood peak. In a normal to high flood year the concentration may reach 0.4 percent by weight for a few days. The concentration then gradually falls off until in December it again becomes less than 0.01 percent. Simaika (111, p. 18) gives a diagram of the sediment load of a typical year, 1931, on the Nile at Halfa (fig. 37).

The original Aswan Dam, about 6,400 feet long, was completed in October 1902 and had a capacity of 865,000 acre-feet. In lieu of a spillway, 180 sluices, capable of passing a maximum flood of 500,000 second-feet, were built into the dam in 4 groups at different levels (117, pp. 155-157). The first group, consisting of 65 gates, extended from the bottom of the river to a height of 22.96 feet. The second group, consisting of 75 gates, extended from an elevation of 14.76 feet to 37.72 feet above the river bed. These 2 groups of gates were 6.56 feet wide and 22.96 feet high. The third group of gates, numbering 18, extended from a bottom elevation of 27.88 feet to a top elevation of 39.29 feet. The fourth group of gates, 22 in number, extended from a bottom elevation of 41 feet. The third and fourth groups

were 6.56 feet wide but only 11.48 feet high. The arrangement of these gates is shown in figure 38.

In the first stages of the flood the upper gates are opened. After the lake level has been lowered a certain amount, the next group of gates is opened, but water is not discharged through any but the upper gates under the maximum pressure head.

During 1907-12 the dam was raised 22.9 feet to provide a storage capacity of 1,970,000 acre-feet, and during 1929-31 was further raised to an elevation of 400.3 feet to give a capacity of 4,400,000 acre-feet.

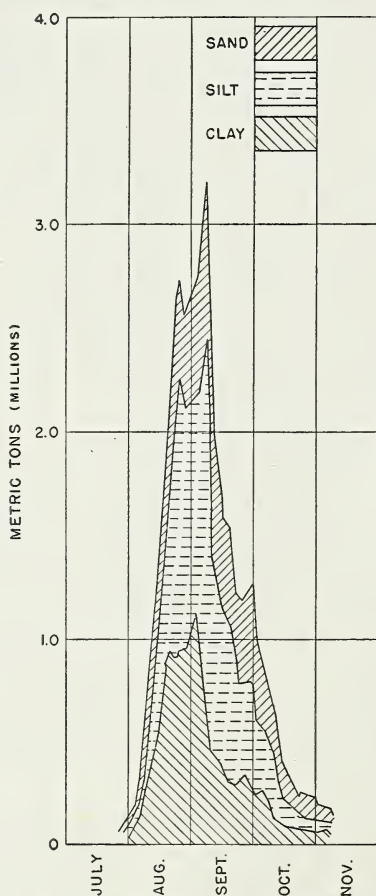


FIGURE 37.—Distribution of total suspended sand, silt, and clay in the discharge of the Nile River at Wadi Halfa, Egypt, in 1941. (After Simaika.)

Before the last raising, no evidence of permanent sedimentation in the reservoir had been noted. Subsequently, however, the date at which the gates are closed in order to fill the reservoir completely by the end of the flood season has been advanced from December to about the middle of October. Previously, only the waters of the White Nile were stored for irrigation, and the floods of this river occur in December, whereas the floods of the Blue Nile are not completely passed by the end of October. Recent studies have indicated that

some net deposition may be occurring now, although the amount is so small that it may be within the limit of error of the measurements.

An estimated 23,000,000 tons of sediment was deposited in the reservoir during the period August 21 to November 16, 1938 (*111, p. 52*). The proportion of sediment trapped will probably increase in the future, as the date for closing the gates will have to be advanced still further to meet the expanded irrigation programs contemplated. In fact, filling during years of low flow may have to start at the crest of the flood. Although the annual suspended load of the Nile above Aswan is large, it is only one-tenth as much per unit of drainage area as that of the Colorado River above Boulder Dam.

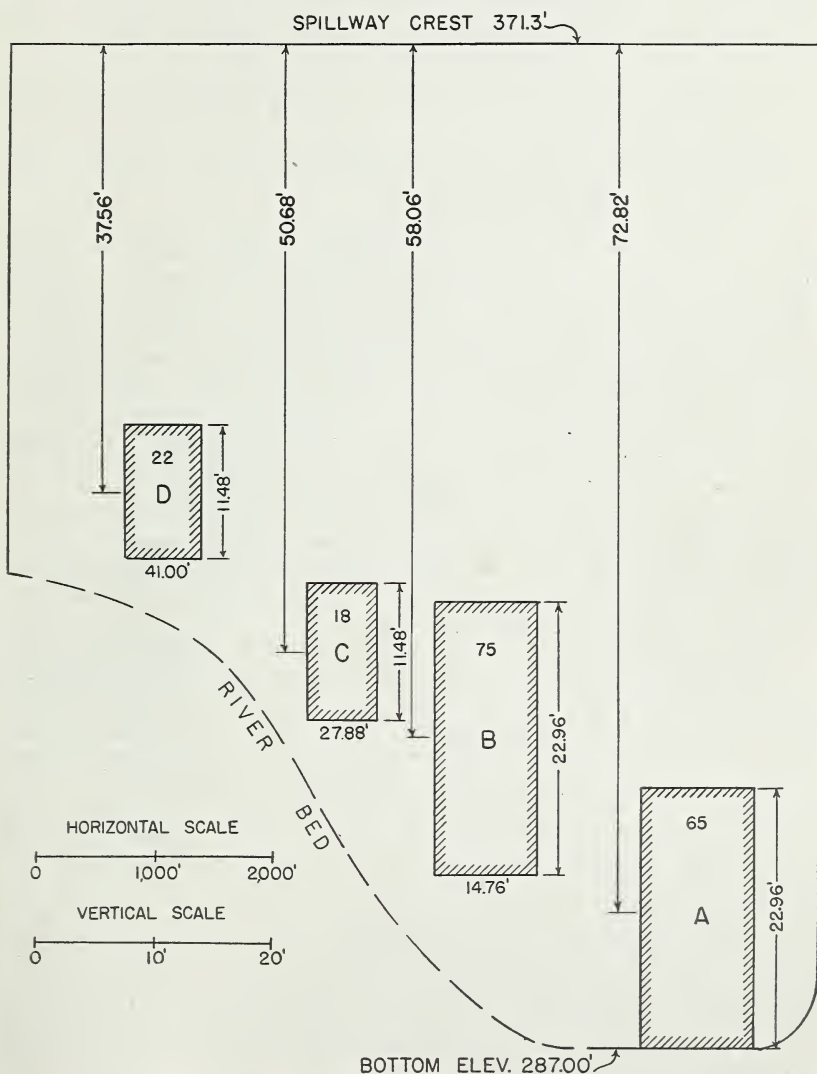


FIGURE 38.—Plan showing arrangement of sluice gates at Aswan Dam on the Nile, Egypt. (After Taylor.)

Dare (41) gives the results of a carefully controlled practice of waste-water release at the Burrinjuck Reservoir on the Murrumbidgee River in New South Wales, Australia. The Burrinjuck Dam, constructed from 1908 to 1920, is 247 feet in height above foundation and creates a reservoir that had an original storage capacity of 771,641 acre-feet at spillway elevation, 1,180 feet. Outlets in the dam consist of four 4½-foot-diameter pipes at elevation 980, two 10- by 6-foot Stoney sluices at elevation 1,050, and one 15- by 8-foot Stoney sluice at elevation 1,140. Measurements of water and sediment inflow to the lake during the period July 1, 1910, to June 30, 1924, showed an estimated total inflow of 14,671,970 acre-feet of water and 6,520 acre-feet of sediment from a drainage area of approximately 5,000 square miles. This represents an average sediment concentration of 0.0444 percent, based on an average dry weight of 64.16 pounds per cubic foot. During the last 8 years of this period the outflow was sampled and found to contain an average of 0.0249 percent of sediment. As the inflow is highly variable and seasonal, a large part coming in flood flows, the outlet gates could be operated to waste the early part of flood flows. The sediment load is mostly fine material.

Jordana (77) claimed that large-capacity sluices in the dam of La Peña Reservoir on the river Gallego, a tributary of the Ebro, Spain, not only kept the reservoir free of sediment but actually resulted in increasing the reservoir capacity by causing erosion of original bed material. The Gallego is subject to large floods that transport heavy sediment loads. The La Peña Dam, creating a reservoir of 20,312 acre-feet, was completed in May 1923 and was equipped with two galleries, each containing three sluices, which are capable of evacuating ordinary floods with little backwater. After each draining, the old river bed was freed of sediment by the current as shown by the clean bed gravel and banks of marl. The conclusion that the capacity of the reservoir increased was based on comparison of original survey data and water releases measured when the reservoir was drained. Because of this, and the fact that observations covered a period of only 1 year, there is some doubt that his conclusion might still be valid.

According to Meyers (89), even when most of the sediment is gravel or pebbles, sluicing gates can be effective in reservoirs on steep torrential streams. He cites a dam 66 feet high on an Alpine brook, Dornbirner Aache, Austria, where the "spacious sluicing arrangement," left open in heavy floods, permitted the "rolling stones" to pass through. The reservoir was filled with water in small storms.

Appraisal.—Controlling sedimentation by controlling waste-water release is obviously possible only when water can be or must be wasted. The method is applicable only when a reservoir is of such size that a small part of large flood flows will fill it. Under these conditions, the development of low permanent dams with high spillway gates or high dams, pierced by large floodgates, would seem to offer a relatively satisfactory solution to the sedimentation problem. Either type of gate is expensive to install and operate; their use generally boosts the initial cost of the storage development. By prolonging the life of the reservoir, however, the added cost may be more than offset over the longer period.

In this country, large flood gates would be particularly appropriate for power reservoirs, where only small storage, or pondage, is needed. In fact, Stoney and Tainter gates 10 to 25 feet high are used on many power dams and doubtless are effective in passing part of the sediment load that is carried into the reservoir, thereby reducing the rate of sedimentation that would otherwise prevail. It would appear to be beneficial at some plants, however, if the flood-release schedule could be readjusted to pass the early part of flood flows with gates wide open and store only the latter stages of the flow. This would require better flow forecasting than is now available on many streams.

Either floodgates of the spillway type or undersluices would also be useful in some water-supply, navigation, and flood-control reservoirs. Certain types of flood-control reservoirs in this country, as, for example, those of the Miami Conservancy District in Ohio, have uncontrolled outlets that pass flood flows at a fixed rate. A very small rate of sedimentation in the Miami reservoirs suggests that similar openings, controlled by gates, might have desirable effects in other types of reservoirs. As most irrigation reservoirs in this country are planned with a view toward storing a relatively high proportion of the total annual runoff, the use of floodgates would not be generally feasible. If the dam is built primarily for diversion or channel storage, however, such gates would be useful.

One problem connected with tall gates is the mechanics of raising and lowering them rapidly. Edgecombe notes that, if instead of using slowly moving cranes, some satisfactory mechanical device could be introduced to open and close the gates rapidly, their height could be increased, which in turn would increase the storage that could be preserved in the reservoir.

REMOVAL OF SEDIMENT DEPOSITS

The removal of sediment deposits from a reservoir may be accomplished by a variety of mechanical and hydraulic methods, which have been variously described as excavation, dredging, siphoning, draining, flushing, flood sluicing, and sluicing aided by such measures as hydraulic or mechanical agitation or blasting of the sediment. All of these methods are measures aimed at recovering storage space behind the dam after it has been lost through the deposition of sediment.

The removal of sediment deposits implies, in general, that the deposits are sufficiently compacted or consolidated to act as a solid, and therefore are unable to flow or move under their own weight. The removal of fluid or semifluid mixtures of mud and water is considered to be a feature of the control of sediment deposition. It has been found that on the bottom of most reservoirs there is a complete gradation between the fluid layers of high sediment content, which can be withdrawn from bottom gates, and the firmly compacted sediment beneath, which will move only in response to mechanical or hydraulic pressures applied to it. Some of the methods described here require that the sediment be placed in a state of suspension in order to permit its withdrawal from the reservoir. Thus withdrawal itself may involve methods identical with those used to remove sediment before it has settled and become firmly compacted.

EXCAVATION

Excavation is the removal of sediment from a reservoir basin by hand- or power-operated shovel, dragline scraper, or other mechanical means. The methods involve draining most, or all of the water from the basin. Most of the reservoir excavations that have been recorded appear to have been justified by some special conditions that left few, if any, alternatives to be considered.

In 1877, 8,000 cartloads of mud were hauled from Bernhart Reservoir, one of the sources of water supply for Reading, Pa. (1). In 1892, a large amount of debris was excavated from the Kittanning Point Reservoir at Altoona, Pa. (2). In this operation 30 teams were put to work hauling away the sediment and dumping it onto 3 or 4 different places above the reservoir. Because of the large amount of organic material contained in the accumulation, however, objections were raised by local residents to the odor of the dumped material, and the operation was consequently abandoned. It is reported that similar excavations had been made previously without objection, in water-supply reservoirs at Jeannette, Pa., and Sing Sing, N. Y.

The Sierra Madre flood-control dam was completed in February 1928 by the Los Angeles County Flood Control District to prevent damage by debris flows into Sierra Madre, Los Angeles County, Calif. The original capacity of the storage basin below spillway level was 49 acre-feet. During the flood of March 2, 1938, this basin received deposits of 38.9 acre-feet, which rendered it almost valueless for further flood protection. During the period July 31–September 22, 1939, the district excavated by power shovels and removed from the basin by trucks a total of 21.2 acre-feet of deposits. The material was hauled to the nearest available dumping ground about 1 mile distant.

During the same period in 1939, 27.3 acre-feet of sediment was excavated from the basin created by the Puddingstone diversion dam on San Dimas Creek. Although exact records of the cost of these operations are not available, it is known that costs of debris removal range from \$0.25 to \$1 per cubic yard throughout this region. The cost of cleaning the Raines Canyon debris basin after the flood of January 1, 1934, was 30 cents per cubic yard (\$484 per acre-foot), and here the material was hauled an average distance of only 500 feet.

The commercial value of sand and gravel sometimes makes reservoir excavation feasible. The city of Pasadena, Calif., has made a practice of selling the deposits in Devil's Gate Reservoir built within the city for flood control by the Los Angeles County Flood Control District. Between 1920 and 1934, more than 47 acre-feet of sediment was excavated by local contractors for building and road construction. Not only was this much storage space gained at no cost to Pasadena, but the city obtained a nominal revenue from this operation.

These examples of excavation involved the use of hand labor or power shovels for loading carts or trucks. Other methods, currently in use for excavation at dam sites or elsewhere might also be used to remove sediment from reservoirs. Lazear (83) has recorded the use of dragline equipment in an irrigation reservoir owned by the Garmesa Orchards Co. at Fruita, Colo. When loss of storage capacity in this reservoir became excessive a first attempt was made to control silting by building a settling basin above the main reservoir. When this had filled within a few years, the owners tried to excavate sedi-

ment with scrapers and teams, but it was found that even after the reservoir had been dry for several months layers of sediment just below the top crust were so wet and mucky that the crust would not hold up a man, much less a team pulling a scraper. As a result, in the spring of 1918, the company installed a dragline outfit consisting of a $\frac{1}{2}$ -cubic yard lever-type bucket on a cable operated by a 50-horsepower engine and a hoist. The excavator was said to handle easily 125 to 150 cubic yards a day. After 2 months of work, a hole 200 by 75 feet in area by 20 feet deep had been excavated. The material was dumped below the main reservoir dam.

The city of Cordell, Okla., excavated considerable sediment from its water supply reservoir in 1926-27 without completely draining it (?). A double-drum tractor hoist mounted on a Fordson tractor was set up on shore where the lake was 450 feet wide and was silted for 800 feet upstream. A bridle cable was stretched across the lake and a Sauerman Crescent dragline scraper was used for hauling out the sediment. The equipment was moved as needed.

Saville (105, pp. 26-27), after studying methods of removing sediment from small power reservoirs on the Deep River, in North Carolina, came to the conclusion that "the use of movable dragline excavators * * * appears to be the cheapest and most feasible method for silt removal in existing ponds." He found that a $1\frac{1}{2}$ -cubic yard excavator could readily be moved from pond to pond and, in most cases, operated economically from the banks. Sand of good quality, for which there was a ready local market, could be taken from several reservoirs and sold to pay, in part, for the cost of excavation. He considered the value of the increased pondage to be worth the remaining cost of operation. Saville estimated that at installations then existing (1922) at least 20,000 horsepower-hours were lost daily for 150 days annually due to inability to store night flow. At as low a cost as one-half cent per horsepower-hour, this amounted to \$15,000 per year. The annual cost of operating the scraper, he estimated, would not amount to nearly this sum when averaged over several years.

Appraisal.—It is readily apparent, from a consideration of the costs involved, that excavation is economically feasible only under very special circumstances. There are few places where excavation by power shovel and dump truck could be accomplished at a cost of less than \$400 per acre-foot of storage gained. Costs for dragline excavation in reservoirs of significant size probably would run at least \$150 to \$200 per acre-foot, even if material could be dumped just outside the reservoir basin. In the excavation of farm ponds by dragline scraper or drag scraper and team, costs as low as 7 or 8 cents per cubic yard, or slightly more than \$100 per acre-foot, have been obtained by the Soil Conservation Service, but not more than a few acre-feet of easily worked soil were excavated, and the material was moved but a short distance.

Where excavated material can be sold for commercial sand or gravel, the cost, if any, to the reservoir owner may be small enough to justify such an operation. Only reservoirs of low capacity-inflow ratio or those on torrential mountain streams contain predominantly coarse deposits, however. The possibility of selling deposits of silt and clay, often high in plant-food elements, for spreading on erosion-depleted soils is also worth investigating.

The excavation of silt and clay, which constitute most of the material in larger reservoirs, is more difficult than the excavation of sand and gravel. Fine-textured sediment cannot be excavated easily from large reservoirs unless it is relatively fluid or relatively compact. In the semifluid state that exists, often for many months, after a reservoir is drained, it will not readily support excavating equipment.

It appears that excavation, in this country, would be useful mainly (1) in relatively small flood-control reservoirs and debris basins, (2) in small power reservoirs where it is important to maintain a certain pondage or regulating pool, and (3) to a limited extent in small water-supply, irrigation, or special-purpose reservoirs. Many water-supply storage or distributing reservoirs, which are generally fed entirely by diversion and have no natural drainage basins, are excavated periodically. A rather extensive literature on costs of excavating this type of settling basin or storage basin may be found in the water-works journals.

One of the critical problems involved in excavation, as well as in other methods of removing sediment deposits from reservoirs, is disposition of the material. As excavations are usually carried out on a comparatively small scale, this problem is not so important as when dredging or sluicing is resorted to, but the cost of land for sediment disposal or of easements for damage must be borne in mind.

DREDGING

Dredging involves the removal of deposits from the bottom of a reservoir and their conveyance to some other point by mechanical or hydraulic means while water storage is being maintained. Certain methods are intermediate between dredging and sluicing, such as those described by Bonnet and Hughes (see pp. 109-110), which involve fixed systems of pipe on the bottom of the lake that permit periodic flushing of bottom deposits through the dam. In this publication such fixed systems are considered as varieties of sluicing, and flexible systems are considered as dredging.

Dredging practices may be divided in three main classes: (1) Mechanical dredging by bucket, ladder, or clamshell and barge; (2) suction dredging with a floating pipe line and a pump usually mounted on a barge; and (3) siphon dredging, with a floating pipe extending over the dam or connected to an opening in the dam, and usually with a priming pump on a barge.

A Board of Army Engineers considering plans for San Carlos Reservoir on the Gila River, Ariz., in 1913 (*123*, p. 44) concluded that the use of ladder or suction dredges would be the most feasible of a number of suggested methods of sediment removal, and that the most effective means of conveying the dredged material to the dam for disposal downstream, with an average haul of about 4 miles, would be self-propelled barges rather than pipe lines and pumps.

Hughes, in an appendix of the Army Board's Report (*123*, p. 152-153), estimated that annual dredging of 6,000,000 cubic yards would cost not more than 5 cents per cubic yard (\$80 per acre-foot), including interest and depreciation at 10 percent on a dredging plant to cost \$1,200,000, which included \$200,000 for a small hydroelectric power plant at the dam. He emphasized the fact that power, which constitutes so large a part of operating expenses, would be provided either directly or indirectly by the water power at the dam.

Hughes pointed out that the discharge of sediment from the reservoir should be nearly proportional to the discharge of water, for otherwise there would be a likelihood of raising the river bed below the dam.

The dredge could be operated, however, on one, two, or three 8-hour shifts, thus making it possible for the output of the plant to vary with the amount of water to be discharged from the reservoir. Furthermore, he concluded that it would be cheaper in first cost and more economical in operation to have two dredges of comparatively large capacity rather than, say, six dredges of one-third the capacity.

In Hughes' plan, dredging would cover an area of 7,500 acres nearest the dam; the remote parts of the reservoir would be abandoned, for the principal item in the operating cost, whatever the mode of dredging, would be conveyance of the sediment. Dredging would not extend into all indentations of the shore line. The floor of the area of desilting would be maintained at an average elevation of 10 feet above the original valley floor, partly because of irregularities in the topography and partly because, at any time, only a portion of the area would be down to grade, the remainder being "bank" 10 to 20 feet high, which could be dredged more economically than the flat surface of the sediment.

Dredging of the Booyens Spruit Reservoir, the main source of water supply for the gold mines controlled by Rand Mines Ltd. in South Africa, has been one of the largest operations of mechanical reservoir dredging in recent years (11). The original capacity of this reservoir is reported to have been between 3,000 and 3,500 acre-feet. With the passing of the years, waste from soil erosion and slimes from surrounding mine dumps reduced the capacity, until in 1934 it was only 528 acre-feet. As a result, dredging operations were begun in December 1934. The equipment used consisted of one Diesel clamshell dredge with a 35-foot boom and a $1\frac{1}{2}$ -cubic yard bucket mounted on a Diesel-operated tug, three 60-cubic yard hopper barges, and one Diesel clamshell dredge with a 50-foot boom and a $1\frac{1}{4}$ -cubic-yard bucket mounted on caterpillars, and operated from shore.

The clamshell dredge mounted on the tug dug and elevated sediment from a maximum depth of 35 feet below water level and discharged it into the barges. The fully loaded barges were then towed by the tug to a position alongside the dam where the caterpillar-mounted clamshell operating on top of the dam emptied the barges, and dumped the sediment over the dam onto a limited dumping area. Later when this dumping area was filled, the caterpillar clamshell would move from the dam to the foreshore, where it would discharge the sediment through a hopper bin into 1-cubic-yard tip wagons, which would transport and dump the sediment onto the adjoining flats. In the 6 months following December 1934, 2 shifts per day were worked, after which 1 shift per day was worked for another 7 months. During this period 152 acre-feet of sediment was removed from the reservoir. It was intended at that time to continue these operations until approximately four times this amount had been removed. The average cost of dredging during the 13-month period was \$0.096 per cubic yard (\$155 per acre-foot), which included all charges except depreciation and interest on the equipment.

One of the earliest recorded suction dredging operations on a reservoir was that by the city of Baltimore, Md., in Lake Roland, one of its

early water-supply reservoirs. City records show that excavation by wheelbarrow and cart was begun in July 1872,¹⁸ but in a few years was superseded by suction dredging, which was continued intermittently thereafter for many years. By 1900 at least 142 acre-feet of sediment had been dredged from this reservoir at an average cost of \$322.41 per acre-foot.¹⁹ This cost, equal to \$0.1974 per cubic yard, is based on the contract price of a dredging company but included, in addition to dredging, a trimming up of the slopes around the lake.

The original Loch Raven Reservoir, built by Baltimore on the Gunpowder River in 1881 with a capacity of 1,565 acre-feet, was reduced by silting to 239 acre-feet in 1900, although some material had been dredged from it between 1896 and 1900. In 1900, the city purchased a suction dredge, which was operated continuously until the fall of 1911. The mud from the bottom of the reservoir was pumped through a long pipe-line to a point below the dam. This dredging not only removed sediment equivalent to the entire amount entering the lake during this period but also increased the capacity of the reservoir by 307 acre-feet during the period (133). Operating costs during the first 4 years of dredging averaged \$0.055 per cubic yard, or \$89 per acre-foot. In 1910, however, the operating cost was \$0.099 per cubic yard (\$160 per acre-foot). It seems probable that if amortization of equipment and other costs including overhead were added, the total cost would not have been much lower than that paid (\$0.1974) to the dredging company that previously performed this work for the city.

The most extensive reservoir suction-dredging operation undertaken in the past few years is that on White Rock Lake at Dallas, Tex. The use of this reservoir as a source of water supply was discontinued in 1928, partly because a larger reservoir had been built to meet the increased demands of a growing city, and partly because silting had reduced the capacity of White Rock Lake by more than 15 percent in 18 years. After 1928, White Rock Lake rapidly became a popular recreational spot, and has enhanced the value of nearby property by an estimated \$10,000,000. By 1937, silting and unhealthy swamping had become so pronounced in a large area in the upper part of the lake that an 8-inch suction dredge (fig. 39) was constructed to cut channels through the reservoir delta and dump the sediment on islands that could be beautified for recreational use. A $\frac{3}{4}$ -yard dragline was used to a lesser extent.

According to records of the Dallas Director of Parks, approximately 86 acres were reclaimed in the lake and 583,320 cubic yards of sediment were moved. The original cost of the dredge was \$33,656.34; the cost of its operation for about 3 years was \$74,940.96; the cost of the dragline was \$6,913.90; and the cost of its operation was \$7,489.23; making a total cost of \$123,000.43. Deducting \$5,000 received by resale of the dragline and allowing \$5,000 for the resale value of the dredge, the total cost of the project was \$113,000. The cost per cubic yard moved was \$0.1937, or approximately \$312.50 per acre-foot. It should be noted, moreover, that sediment was not moved out of the reservoir, but was moved only a few hundred feet, on an average, to the main-made islands within the lake.

¹⁸ See footnote 5, p. 8.

¹⁹ BALTIMORE WATER BOARD. REPORT OF THE WATER BOARD, 1900. Ann. Rpt. Water Dept., Baltimore, Md., pp. 3-25. 1901.

Meyers (89) and Orth (95, *p.* 355) have outlined an almost identical scheme, known as the "Jandin" method, for siphoning material through the dam. Orth considers this method much better than the rigid system of Bonnet (see *p.* 109). Jandin, an engineer, developed and used this method during a period of 3 years, 1892-94, to remove sediment from the Djidiouia Reservoir in Algeria. This reservoir, built in 1873-75 for water supply, had an original capacity of 2,025 acre-feet, which was seriously depleted within 10 years after construction. The content of sediment in the inflow is reported to average about 3 percent [by volume?], with a maximum concentration of 7 percent during flood flows.

Two sluice gates, 3.77 feet in diameter, in the base of the dam, were not adequate to prevent rapid silting. In 1892 Jandin contracted to remove 972 acre-feet of deposits at a cost of \$24 per acre-foot. His



FIGURE 39.—Dredge boat on White Rock Lake, at Dallas, Tex.

scheme consisted of a flexible pipe, 24 inches in diameter, capable of discharging 54 second-feet under normal operating conditions, passing from an opening in the base of the dam to free-floating, sheet iron pontoons, which permitted the pipe to be moved around the reservoir within a radius of about 1 mile. A turbine, installed near the mouth of the pipe and actuated by the pipe-line flow, was coupled to a wheeled chopping instrument near the intake end of the pipe, which was designed for stirring up the sediment.

In the radius of action of the equipment, the deposits were 48 to 52 feet thick and were rather compact in their lower part. Water was sufficient for the desilting operations only in the spring during floods of relatively short duration. Nevertheless, in 3 years, 1,135 acre-feet of silt and clay was removed; but of this amount, only 405 acre-feet was estimated to be previously accumulated deposits, the remainder having come in during the years of operation. The obvious defect of the system was the amount of water required for successful operation.

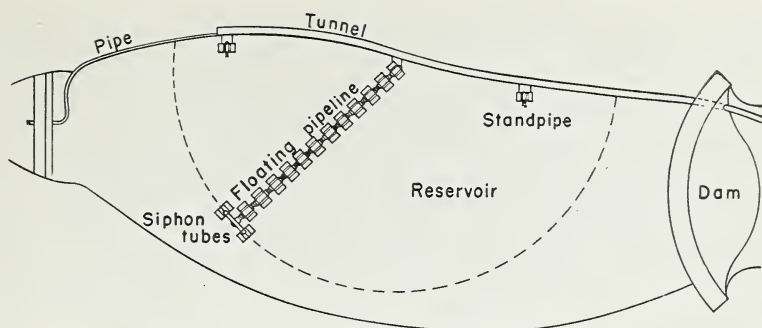
On the basis of his experience, Jandin proposed that the dam be raised 26 feet to increase the capacity from that remaining in 1894, 567 acre-feet, to 6,485 acre-feet. This would make the reservoir larger than just sufficient to supply the necessary irrigation needs, which is apparently a requirement for the operation of such a method. The operations had shown that so much water was required to loosen and remove the old compacted sediment that Jandin proposed, henceforth, to concentrate primarily on removing the incoming sediment before it had an opportunity to compact; and only during unusual floods, when ample water was available, would an attempt be made to work in the old material. The proposed scheme would have a pipe line, $1\frac{1}{4}$ miles long, increasing in diameter toward the dam from 1.31 feet to 3.28 feet. To this pipe line would be attached 100 branch lines, 66 feet apart and 5 inches in diameter, extending from the lake surface to approximately the level of the sediment. By moving the pipe line in the radius of the action, all sediment in the lower part of the reservoir would be within effect of suction. It appears that in this reservoir, density currents were operative and accounted for accumulation of most of the silt and clay in the lower part of the reservoir basin. Jandin computed that in a reservoir of 115-foot depth, this system would use 35 to 141 second-feet of water, according to the reservoir stage.

Jandin estimated that the cost of the plant would be about \$50,000; the operating cost about \$5,000 annually. Adding 12 percent for interest, amortization, and maintenance, he estimated the total annual cost to be \$11,000.

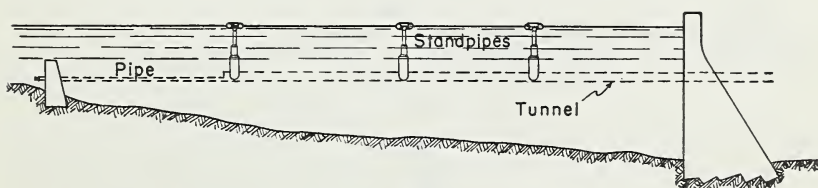
Vogt (131) has described another siphoning method involving the following features: A large tunnel would be driven through wall rock or a conduit would be laid along one of the side slopes of the reservoir basin. The lower end of the tunnel or conduit would go through the dam or through rock to which the dam was buttressed, so that water released from the tunnel could be diverted into canals or allowed to flow downstream. The tunnel would extend up the basin to within less than a mile of the upper limit of the desilting area, at which point it should be on the elevation of the reservoir floor. From the end of the tunnel, however, a pipe would extend to a small upstream dam designed to give a water head of 20 feet in the tunnel. In a reservoir more than 160 feet deep at the dam, the bottom of the tunnel would be 40 feet below the reservoir surface. The tunnel would have no grade (fig. 40).

Standpipes would be connected to the tunnel at intervals determined by the effective radius of action of the sediment removed apparatus (about two-thirds of a mile). Telescoped into the standpipes would be vertical pipes, or risers, revolving on their axis and held up by floats, which would thus allow continued functioning with fluctuation of water level (up to 13 feet in Vogt's illustration). A flexible-joint pipe line, mounted on floats, riding just beneath the water surface, would connect the risers with the siphon tubes.

The siphon tubes would be hung from floats, beneath which a car frame is supported by cables or drawbars and is raised and lowered by counterweights mounted on a drum. The car frame carries the lower half of a siphon tube, which is telescoped into the upper half suspended from the float. The car frame glides over the surface of the sedi-



A. Plan view



B. Cross section

FIGURE 40.—Plan of siphon dredging. (After Vogt.)

ment and is so balanced by the weights that it changes elevation as needed.

The lower end of the siphon tube is bent in a right angle so as to point toward the direction of travel. According to Vogt, the difference in pressure between the reservoir water and water in the tunnel would draw the car frame forward. A chain and hook suspended from a chain wheel on the car frame is used to remove obstacles such as limbs and brush lodged in the sediment. It also stirs up the sediment somewhat.

Considerable point is made of gas in the sediment and the necessity of having a "self-deaerating" siphon.

For a "typical" reservoir as shown in figure 40, A, Vogt concludes that with a 3.28-foot diameter pipe line, with a radius of action of 3,280 feet, a maximum depth to sediment of 164 feet, water level in the tunnel 32.8 feet below the top of the dam and a difference of 20 feet between water level in the upper basin and main reservoir, the plant could discharge 48 second-feet, removing a little more than 4 acre-feet of sediment per 24 hours. He estimated the initial cost of the installation to be \$283,010, and the annual operating expense and interest (at 10 percent) and depreciation (at 4 percent) for operating on one 8-hour shift 300 days as \$50,537. The cost of desilting would thus be \$0.26 per cubic yard (\$419 per acre-foot). On a 24-hour working schedule the cost could be reduced to \$0.14 per cubic yard (\$226 per acre-foot).

Sergaev (110) described a proposed siphon dredging scheme for desilting off-channel reservoirs on the flood plain of the Murghab River in Turkestan, U. S. S. R. The main features of this scheme (fig. 41) are a pipe line with flexible joints (*a*), extending from the river (*b*) through the earth embankment (*c*) of the reservoir to a float consisting of two long narrow boats (*d*), similar to canal boats, held rigidly several feet apart by cross bars (*e*). A rotating shaft (*f*) extending between the inner edges of the boats is so rigged as to form a hand-operated windlass for raising and lowering a flexible suction pipe (*g*). The nozzle of this pipe (*h*) is protected against sucking in large debris by an angle-iron grid (*i*). Above the nozzle mouth

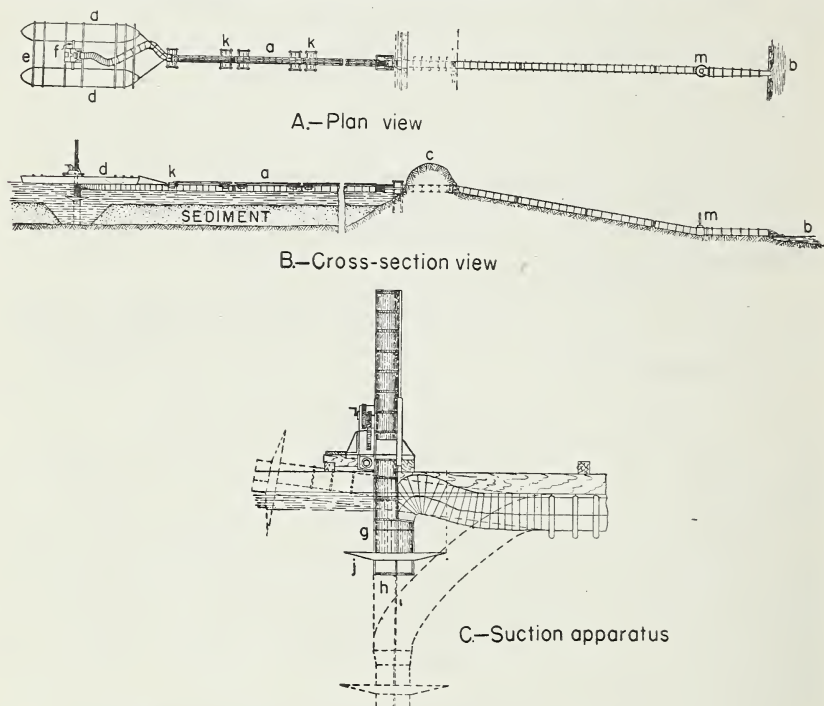


FIGURE 41.—Plan of siphon dredging. (After Sergaev.)

is attached a rather flat, hollow, truncated metal cone (*j*) with its wide base turned upward. This cone prevents the nozzle from sucking water from immediately above it and spreads the suction to a greater area, thereby pulling in more sediment. By changing the distance between the lower side of the cone and the bottom of the reservoir, it is possible to regulate partially the velocity of inflow and sediment concentration.

As the pipe is held by pontoons (*k*) just below the water level in the reservoir and as the river end of the pipe is well below reservoir surface, the apparatus acts as a siphon. A valve (*m*) is installed in the pipe near the river end, however, so that it may be primed with water, if necessary to start the siphonic action. The author claims that his method will clean sediment from a reservoir at a cost equiva-

lent to \$4.84 per acre-foot, including amortization of equipment. It seems extremely doubtful whether such a low cost could be obtained, even for operating expenses, under the American economic system.

Saville (105, p. 26) discussed pumping from a floating dredge on small power reservoirs in North Carolina. This method would be advantageous, he says, because both sand and silt could be dredged, the sand automatically separated for commercial uses, and the silt pumped to farms for fertilizing purposes. The chief difficulty in small reservoirs, however, would be that of moving a pumping unit from pond to pond. Cost would make it impracticable to use a separate unit for each pond.

In 1940, 33,506,651 cubic yards of material was dredged at an average cost of \$0.176 per cubic yard on 93 Federal river and harbor dredging projects on the Atlantic and eastern Gulf coasts. The dredging involved movement of 50,000 to 2,000,000 cubic yards per project and was done by all types of equipment, including hopper dredges, clamshell dredges, and pipe-line suction dredges. Costs ranged from as low as 4 cents to as high as 67 cents per cubic yard but were not proportional to the amount of material dredged.

The Army Engineers' estimate for maintenance dredging on all Ohio River navigation pools is \$0.225 per cubic yard.

Appraisal.—Dredging, even on the smallest scale, entails expenditures of several thousand dollars for equipment, and the equipment generally available today cannot be readily transported from one lake to another. Therefore dredging operations are usually undertaken only on lakes of considerable size, and when a relatively large quantity of sediment, ordinarily several hundred acre-feet annually, is to be removed.

The minimum operating costs on the larger-scale dredging projects may be expected to run at least \$50 per acre-foot of storage space recovered. Including amortization of equipment and depreciation, overhead, and other expenses, it seems unlikely that total costs would run much less than \$150 per acre-foot. Actual costs on various projects have been given in this chapter.

Dredging, in common with most other forms of sediment removal, becomes more costly as the deposits become more compact. The costs are still further increased if vegetation such as tamarisk has grown up within the reservoir area, as it has in San Carlos and Elephant Butte Reservoirs.

From available records, it appears that dredging has been most often undertaken because of a desire to maintain a lake at some particular location, rather than merely to maintain a certain storage capacity. Water filtration plants, for example, are often adjacent to water supply reservoirs. The cost of building new filter plants or laying long supply lines to the nearest available replacement reservoir site, added to the cost of constructing the new reservoir, may be greater than the cost of dredging. A recreation reservoir, such as White Rock Lake, may be dredged to maintain surrounding property values, not to gain storage space. A reservoir such as Carnegie Lake (63) at Princeton, N. J., used for collegiate rowing, may be dredged because it is adjacent to the University, although this operation may be more expensive in the long run than building a new reservoir some miles distant.

Numerous authors have expressed the opinion that at the present time dredging is not economically feasible for most water-storage projects, that is, the return from services rendered by these projects will not stand the cost of sediment removal by dredging, but costs may become justifiable as sites become scarcer and the value of their services increases.

The ultimate value of reservoir sites must be measured by the lowest cost for sediment removal and disposal less the return, if any, from sale of the material for construction or for soil improvement and land reclamation. Undoubtedly some form of dredging will eventually prove to be the cheapest widely applicable method of sediment removal.

Orth (95, p. 356) gives the following appraisal of dredging, based on European experiences:

Dredgings of storage reservoirs are undertaken in cases where the building of a bypass is impossible and where flushings are not successful * * * Mostly used are floating dredges, bucket-chain dredges, or best, suction dredges * * * dredging at greater depth [than 131 feet with special dredges] would prove uneconomical or impossible * * *

The disposal of the dredged material, of course, has its difficulties. * * * it is rarely profitable to use these ideal substances for building purposes because of the distance between the dredging place and the site of the building. Another disposition is to return the sediment to the stream below the dam, but this also has its drawbacks in the fact that the stream because of the heavy loss of water in the reservoir does not retain enough transporting capacity to move the dumped sediment * * *

Dredging is a continuing work * * *

DRAINING AND FLUSHING

Draining and flushing involve the relatively slow release of all stored water in a reservoir through gates or valves located near the bottom of the dam, and the maintenance thereafter of open outlets for a shorter or longer period during which normal stream flow cuts into or is directed against the sediment deposits. Draining alone will generally remove some sediment, even if the gates are closed to begin storage again as soon as all water has been released. If a stream flow not greater than the gate discharge capacity is coming into the reservoir, much more sediment will be removed if the gates are left open for a period of time, thus allowing the flow to scour out a channel in the sediment deposits through the lake basin. A still larger amount of sediment will be removed if the current is directed against the deposits at various points after the initial channel is cut.

The highest rate of sediment removal from draining alone will be obtained in the first few days or weeks after all stored water has been released. As soon as the stream has reestablished approximately its original gradient through the reservoir basin, the amount of sediment picked up and transported will greatly decrease, for only by the slow process of lateral swinging and broadening of its channel can the flow acquire more load. Simple and inexpensive baffles, dikes, or retards may be used for diverting the flow against the banks of sediment after the initial channel has been cut. If these are frequently moved, if the inflow is satisfactory, and if the process is continued long enough, relatively large amounts of sediment may be flushed out of the basin.

Another important effect of complete or even partial drainage of a reservoir is the compaction of fine sediment resulting from its

exposure to air drying. Under some circumstances the increase in effective storage space because of compaction may be so large as to warrant draining for this purpose alone.

Recent draining and flushing operations at seven of the flood-control reservoirs constructed by the Los Angeles County Flood Control District in the San Gabriel Mountains in California resulted in increases of capacities that had been seriously depleted by the very heavy debris loads transported into these reservoirs during the flood of March 2, 1938 (20 a).

Big Tujunga Reservoir, on Tujunga Creek, which was completed in July 1931 with an original capacity of 6,240 acre-feet, contained 1,506 acre-feet of sediment below spillway level after the flood of March 2, 1938. During the winter seasons of 1939-43, when the reservoir was drained, normal stream flow flushed 65 acre-feet of sediment through a 48-inch gate in the lower part of the dam. The flushing was assisted by building small training walls that diverted the flow into the banks of sediment.

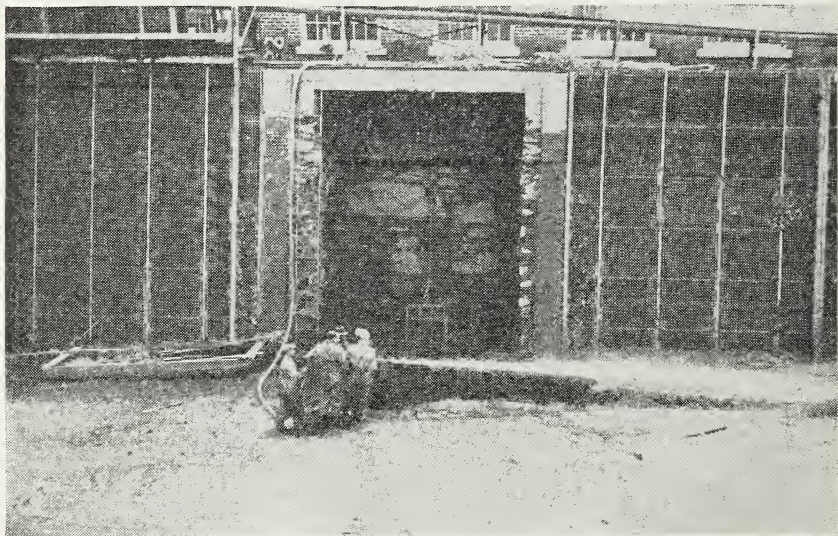
Santa Anita Reservoir on Big Santa Anita Creek was completed in March 1927 with an original capacity of 1,043 acre-feet. Surveys after the flood of March 2, 1938, showed 360 acre-feet of sediment in the basin. During the winter of 1939-40, 146 acre-feet of sediment was flushed through a 30-inch opening in the dam, and this resulted in a net increase in capacity of 27 acre-feet below spillway level, and an additional 17 acre-feet to the top of the dam.

San Gabriel No. 2 Reservoir, on the West Fork of the San Gabriel River, was completed in April 1935 with an original capacity of 12,298 acre-feet. A survey after the flood of March 2, 1938, showed that 1,533 acre-feet of sediment had been deposited. During the summer and fall of 1939 draining and flushing through valve-controlled openings into a 14-foot diameter outlet tunnel resulted in the removal of 242 acre-feet of sediment, or 15.8 percent of the accumulation below spillway level. This represented an increase in the available capacity of 2.24 percent. In the water year 1939-40, 42 acre-feet of sediment was flushed through the dam, but sediment entering the reservoir caused a net decrease in capacity between November 1939 and October 1940 of 82 acre-feet. Sluicing in the 1941-43 seasons removed 105 acre-feet.

Baumann (20a) reports a total sediment removal equivalent to 1,712 acre-feet involving a total stream flow of 24,102 acre-feet. The quantity moved was estimated from frequent sampling of the outflow, which showed a sediment load ranging from 5 to 25 percent by volume and averaging 7 percent. The cost of the flushing operations, mainly for labor, was \$22,765. The costs ranged from \$4.36 to \$59.69 per acre-foot removed in the seven reservoirs. The average cost for the total removal was \$13.23. These figures do not include the cost of removing floating debris, which is often necessary before the reservoir can be drained for flushing. The cost is about equal to that for flushing. Furthermore, in some cases, channels below the dams were of insufficient grade for the flushing discharge to carry through more than half of its sediment burden. In such cases, mechanical excavation of the channels was necessary. Costs of this work ranged from \$0.21 per cubic yard for simple casting to \$0.38 per cubic yard for haulage to a disposal area about 2 miles away.

The most favorable time for draining and flushing in southern California is during the long dry period that follows the flood season. The dry period usually begins in April, and extends until December, although occasionally floods have been experienced as early as September. During April, May, and June residual runoff furnishes optimum conditions for flushing. A stream discharge of approximately 25 or 30 second-feet was found to be required for flushing in the Big Tujunga Reservoir, whereas in Santa Anita Reservoir 10 or 15 second-feet were satisfactory. The reservoirs cannot be kept completely drained during periods when storms may occur, because a flash runoff would redeposit material against the dams and clog up their outlet works.

During a survey of the Washington Mills Reservoir on the New River, near Fries, Va., by the Soil Conservation Service in 1936, it was possible to measure the effect of a complete drawdown (34). This reservoir was completed for power generation in November 1902, and had an original capacity of 2,954 acre-feet of which 82.69 percent had been lost at the date of survey. On April 17, 1936, during the survey, soundings were taken in the lower 2,400 feet of the reservoir. On April 18, five 4- by 16-foot head gates leading to the forebay of the powerhouse, and five similar head gates diverting water from the forebay back to the river were opened at 7 a. m. By 4 p. m., when the gates were closed, all stored water had been released and a normal stream current was flowing through the gates. In the meantime hydraulic sluicing had been used to clear sediment from in front of the gates, but the amount removed by this sluicing was negligible (fig. 42). The gate sills are 20 and 22 feet above the original stream bed and 18 and 20 feet below the crest of the dam.



5397

FIGURE 42.—Sluicing sediment from in front of gates, Washington Mills Reservoir on the New River, Va.

A resurvey of the lower area of the lake on April 23 showed that 6.76 acre-feet of sediment had been flushed from the reservoir as a result of this drawdown. This was 2.77 percent of the deposits in the lake prior to drawdown. The large size of these gates increased the rapidity of drawdown, and hence the amount of sediment removed. On the other hand, their elevation above the original stream bed level, and their closure very soon after drawdown was completed, tended to counteract their large size.

An illustration of the effect of draining on compaction is given by Nickle in his discussion of Stevens' paper (113, pp. 252-253). He reported that a sedimentation survey of Medina Reservoir, about 35 miles northwest of San Antonio, Tex., made in September 1925, revealed 2,692 acre-feet of deposits, which had an average dry weight per cubic foot of 30 pounds, and a texture so fine that 99.5 percent passed a 300-mesh sieve. Five years later, however, the average dry weight was estimated to have increased to 63.6 pounds per cubic foot as a result of exposure of the sediment to air drying at various times during this period. In other words, the 2,692 acre-feet of sediment measured in 1925 had shrunk 53 percent to 1,270 acre-feet.

Appraisal.—Draining and flushing can be practiced only when it is possible to release all of the water stored in a reservoir. Flood-control reservoirs in regions of highly seasonable storm occurrence, as those in Los Angeles County, Calif., if equipped with suitable bottom gates, are well adapted to draining and flushing. Because reservoirs in the Los Angeles area have a value in increasing ground-water storage, however, it is undesirable to release water from them at a rate so large that it cannot percolate into the stream channel beds. Even though complete reservoir drainage cannot be achieved in every year, periodically a runoff season will have such characteristics that water can be completely drained from the reservoir and the gates kept open for a period of weeks or months.

In municipal or corporate water-storage systems, comprising several reservoirs that are not all needed simultaneously, the reservoirs often may be drained alternately to good advantage.

Small power dams should be equipped with relatively large gates, for the purpose of draining and flushing, as well as to permit flood sluicing or to control waste-water release. Saville's study of reservoirs on the Deep River, N. C., indicated, however, that either flood sluicing or controlled waste-water release are more effective than simple draining and flushing. It seems probable that operators of reservoirs on sediment-laden streams would be well repaid in the long run by shutting down the power plant periodically for a sufficient time to permit flushing out as much of the sediment as possible. This is, of course, generally feasible only where the power plant is shut down over week-ends or where it is interconnected to a large system and can be stopped during periods of slack demand.

Hemphill (69, p. 1070), discussing irrigation reservoirs of the Southwest, concluded that although some small reservoirs have been partly cleaned by draining, and by permitting the flow of the stream to scour out the deposits, it is doubtful whether this method would be effective with larger reservoirs. The steam would cut only a narrow channel through the deposits, and the scouring action would cease before any considerable proportion of the deposit had passed out of the reservoir. The practice would be improved by directing the flow

of water against the banks. Another objection to flushing in irrigation reservoirs, he asserts, is that where water is valuable enough to warrant the construction of extensive storage works, it is too scarce and valuable to be used in clearing a partly silted reservoir. This would depend, of course, entirely on the manner of operation of the reservoir. Many irrigation reservoirs are necessarily, or could be, drained at frequent intervals without loss of the water to holders of water rights.

The record of compaction in Medina Lake is probably an extreme case. Practically all of the sediment in this reservoir is very fine textured. The reservoir is subject to a large fluctuation in water level, and evaporation is high. The more nearly a reservoir has this combination of conditions, and the longer the reservoir can be kept drained or at low stage, the more effect may be expected from compaction during drainage or drawdown.

Most of the conditions controlling the effectiveness of sluicing operations, as outlined by Orth (see p. 105), also apply to draining and flushing. The benefits that may be obtained during any reasonable length of time, ranging from days to weeks, would appear to consist of removing 1 percent, or less, of the sediment in most basin-type reservoirs, 3 to 10 percent in moderate-sized channel-type reservoirs, and 25 percent or more in small channel-type reservoirs if a large discharge is available during the period of flushing. On the other hand, compaction will be most effective in basin-type reservoirs and may reduce the sediment volume 1 percent or less in a few days, several percent in a few weeks or months, and up to 50 percent in the course of several years' exposure. Draining and flushing the majority of reservoirs is a simple and inexpensive practice if the water loss can be afforded, but its benefits are often proportional to the low costs.

FLOOD SLUICING

Flood sluicing is the practice of removing sediment deposits from a reservoir through large sluice gates near the base of the dam by utilizing the scouring action resulting from the sudden release of the water impounded in the reservoir or of flood flows entering the reservoir.

There is no exact distinction between the methods described here as flood sluicing and those described under Control of Waste-Water Release (p. 74) on the one hand, and Draining and Flushing (p. 94) on the other. In the writer's classification, the basic principle of the methods described under Control of Waste-Water Release is passing a major part of sediment-laden flood flows through deep spillway gates or large undersluices at a rate of discharge that prevents sedimentation. The methods described under Draining and Flushing involve the slow release of stored water from the reservoir through small gates or valves, making whatever use is possible of the normal or low flow of the river to entrain sediment and carry it through these outlets. In contrast, flood sluicing depends for its efficiency on either the scouring action exerted by the sudden rush of impounded water under a high head through undersluices, or on the scouring action of high flood discharge coming into the reservoir.

Flood sluicing or scouring is one of the oldest methods of reservoir silting control, being secondary only to manual excavation of material,

which probably has been practiced in small storage reservoirs or "tanks" since ancient times. During the Middle Ages a method of sluicing sediment out of reservoirs in southeastern Spain was devised by enterprising Moorish irrigation engineers. Their method, little changed, is still in operation today and, though crude in many respects, has been effective in maintaining the efficiency of certain reservoirs for centuries.

The oldest sediment-scouring device is known as the Spanish gate or Spanish undersluice. D'Rohan (44, p. 57) gives the following description of this method, taken from the writings of Sir William Willcock (see fig. 43, which illustrates the features referred to in this description).

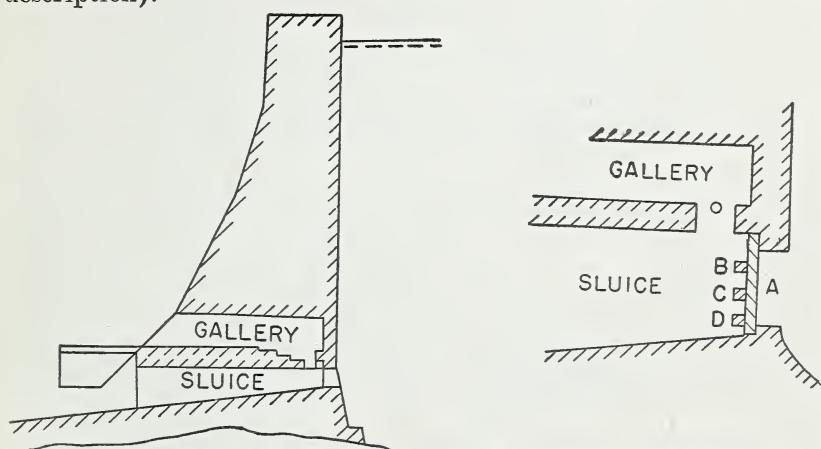


FIGURE 43.—Plan of the original Spanish gate for undersluicing.
(After D'Rohan.)

* * * A Spanish undersluice consists of an opening [near the base of the dam] of from 1 to 3 meters in height, and from 1 to 3 meters in width at the up-stream end; it increases gradually as it advances downstream, and it is sometimes as much as 4 meters wide and 6 meters high. This opening is closed at the up-stream end by a wooden door, called a Spanish door, supported against horizontal timbers let into apertures in the two sides at the point A in the figure. Just above the undersluice is a gallery. This gallery is about a meter wide and 2 meters high, and is closed on the up-stream side, and open on the down-stream face to allow the workmen to enter. It communicates with the undersluice by an opening some 60 centimeters in diameter just down-stream of the gate A.

The door is put in position in the undersluice from the down-stream side when the reservoir is empty, and the three horizontal timbers, B, C, D, are let into slots in the jambs, and the whole door is well caulked. The water now rises in the reservoir and as the deposits accumulate they bury the door and gradually gain great consistency. It takes four years for the deposit to become solid, though it is generally left 10 years. When the reservoir has got filled up with deposits to the extent which is considered a maximum, the workmen enter the undersluice, bore with an auger through the door to be sure that the mud is solid, saw the timbers, B, C, D, and then escape into the gallery. The door is now free to drop, but it is generally held by the solidified mud. The workmen now go to the top of the dam and work a hole through the deposit with a long iron pole until after the water touches the door. When this happens the door falls, and the mud follows it in a tremendous avalanche. The reservoir is soon emptied, and more or less of the deposit removed. What sediment is not swept by the velocity of the current is shoveled into the stream by the workmen. A new gate is then put in, new horizontals, B, C, D, are placed behind it, and the reservoir begins to fill again.

Kanthack (78, *pp.* 222-224) describes the older type of Spanish undersluices, and the method of their operation in the Alicante (Tibi) and Elche Dams in Alicante Province, southeastern Spain. Additional information on these reservoirs has been taken from the accounts of Nagle (92), Schuyler (108), and Wegmann (132, *pp.* 54-57). The Alicante Dam was built between 1579 and 1594 in a narrow gorge of the river Monegre, for irrigation of the plains of Alicante. It has a total height of 146.6 feet and is basically a gravity-arch dam constructed of rubble masonry faced with cut stone. The gorge at the dam site is remarkably narrow, being only 25 to 30 feet wide at the bottom and 190 feet wide at the top of the dam. The reservoir is small for so large a structure. It extends 5,900 feet above the dam, and had an original capacity of only about 2,982 acre-feet. The sides of the reservoir are very steep, and the bulk of the sediment is deposited in the old channel in the most favorable location for sluicing.

The scouring gallery, consisting of a culvert through the bottom center of the dam, is 5.9 feet wide and 8.9 feet high at the upstream portal, but is larger below. The gallery is blocked near the upstream face by a bulkhead composed of vertical wooden beams about 12 inches square, which are installed and held in place in a manner similar to that described by D'Rohan. The sediment in the gallery above the bulkhead compacts very firmly. When the time has arrived for opening the sluice, a man enters the gallery and carefully removes the timber balks or loosens them with an ax. If any movement in the sediment is noted he must escape as fast as he can. If the sediment continues to hold, a special type of drill is worked through a hole penetrating the structure of the dam from the crest to the roof of the gallery.

Kanthack (78, *p.* 223) inspected the Alicante Dam in December 1908, a week after the scouring sluice had been opened for the first time in 16 years. Before opening, the sediment had been 79.5 feet deep at the dam with a depth of water of only 8.6 feet. Within a week the reservoir had been entirely cleared of sediment for a distance of about 300 feet above the dam. Upstream of this point the clearance was only partial but was proceeding by sloughing. The river below the dam flows in a narrow gorge, which was found to be full of mud. Considerable damage had been caused by the sudden release of the water and mud.

In the last century sediment often was allowed to accumulate in Alicante Reservoir for periods of 10 years or more between sluicings. In 1843 when the reservoir had not been sluiced for 14 years the sediment was 75 feet thick. In 4 years, the normal interval between sluicings, the sediment is 39 to 52 feet thick. In order to start the scouring effectively a water depth over the sediment of 10 to 13 feet was needed.

The ancient Moorish regulations decreed that the scouring sluices should be opened every 4 years. Kanthack believes that had this rule been adhered to instead of opening them every 16 years the cleaning would have been more effective. Kresnik (79) reported in 1890 that Alicante Reservoir had been cleaned in one sluicing of an accumulation of approximately 1,612 acre-feet at a cost of about \$1,950. Nagle (92), however, wrote in 1902 "cleaning is done about once every 4 years, and costs only about \$50.00." The same cost figure is given by Schuyler (108, *p.* 252) and D'Rohan (44).

The Alicante Reservoir has been used for more than 300 years as a result of flood sluicing. If flushed every 4 years, during which period 3 to 4 percent of the capacity is generally lost, a water volume equal to 30 percent of the reservoir capacity is said to clean it effectively. The effectiveness of flood sluicing results from a bed slope of 2.33 percent and a maximum reservoir width of only 1,000 feet (*95a, p. 345*).

The famous old Puentes Dam in Spain was built between 1785 and 1791 in a gorge of the river Guadalatin about two-thirds mile below the confluence of the rivers Delez and Luchena. In 1802 it was breached due to foundation failure. In 1885, it was rebuilt on a site a short distance upstream from the original structure. The new dam had a maximum height of 156 feet, and an original storage capacity of approximately 21,465 acre-feet. Its drainage area of about 800 square miles of rough, largely barren, mountainous country produces violent floods and large quantities of sediment. A flood discharge of 66,700 second-feet, or 83 second-feet per square mile, was recorded on September 11, 1891. The normal, dry-weather discharge is only about 15 second-feet.

TABLE 2.—*Sediment sluiced through Puentes Dam, Spain*

Date	Duration of operation	Discharge flowing into reservoir	Sediment scoured out of reservoir	Remarks
		<i>Second-feet</i>	<i>Acre-feet</i>	
January 1893.....	23 hours.....	106	661	Work stopped due to choking of galleries.
December 1894....	23 days.....	282	3,644	
February 1898....	15 hours.....	247	-----	Galleries blocked by 2 large rocks.
November 1898....	10 days.....	141	828	
November 1900....	24 days.....	141	3,627	

Three scouring galleries were built into the new dam, the two near the center being approximately 6 feet 6 inches high and 4 feet wide, and the one near the right abutment being 4 feet 10½ inches high and 3 feet 3 inches wide. All the galleries are controlled by gates operated by hydraulic power.

Table 2 gives a record of the sediment scoured from the reservoir during several openings of the gallery. Despite the frequent sluicing operations during the period 1893–1900, which resulted in removal of 8,528 acre-feet of sediment from the reservoir, the reservoir in 1900 contained 5,670 acre-feet of sediment, an amount equal to about one-quarter of its original capacity (*78, pp. 226–227*).

The periodical cleanings have to be timed, insofar as possible, with reference to irrigation requirements, and 24 days was found to be the maximum period that could be allowed for sluicing. Experience showed that for efficient cleaning a sustained flow of about 100 second-feet was necessary during the second stage of the process after the reservoir had been emptied. For this reason the time for scouring had to be very carefully chosen during a period of the year when the irrigation demand was not very great, and directly after a thunderstorm or, better still, after snow had fallen and was melting over the drainage basin.

According to Nagle (*92*), the Villar Reservoir was constructed between 1870 and 1878 in a gorge on the Rio Lazoya by the Spanish Government to supplement the water supply of Madrid, as well as for

irrigation. The dam is of rubble-masonry constructed 168.6 feet high and created a reservoir of 13,050 acre-feet. The dam has two sluicing galleries with inlets of 20 square feet each, which are set 162 feet below the overflow line. The sluicing outlets are opened and closed by gates operated by hydraulic power from a central tower; but as their openings are small in comparison with the cross section of the lake above, and as the side slopes of the lake are flatter than those of Alicame Reservoir, sediment was removed only from the old stream channel, and high banks of deposits were left on either side. By means of ditches built on each side, and a little above the flow line of the reservoir, water is conducted from a point higher up the stream. By cutting the banks of these ditches, and directing the water along the banks of sediment, some of it can be washed down into the old channel, and through the sluices. This practice moves the sediment rapidly, but it requires a large amount of water, which, because of the smallness of the feeding stream, cannot always be spared.

Schuyler (108, p. 253) records that the reservoir impounded by the 116.5-foot Val de Inferno Dam built in 1791 on the Lucheno River, a tributary of the Guadalantín River, Spain, was entirely filled with sediment, and out of service by 1900. The scouring of sediment through the sluice, which was 14.8 feet high and 9 to 12.3 feet wide, was stopped because of injury to the property below; and hence the structure ultimately had to be abandoned.

The Habra Dam was built on the Habra River in Algeria, between 1866 and 1871. With a height of 116.8 feet and a length of 1,066 feet, it created a reservoir of 24,330 acre-feet, which received drainage from 3,859 square miles. In 1872 it failed and was reconstructed, but again in 1881 it failed with great loss of life. It was rebuilt in 1885. During this interval all sediment previously deposited was scoured out. By 1907, despite repeated sluicings, the capacity was only 10.125 acre-feet.

Two sluice gates, each 4 by 6½ feet, were built into the dam at river level.

Table 3 gives a record of the effects of several scouring operations through these gates (89).

TABLE 3.—*Sediment sluiced through Habra Dam, Algeria*

Date	Duration of operation	Discharge flowing into reservoir	Sediment scoured out of reservoir	Remarks
	<i>Days</i>	<i>Second-feet</i>	<i>Acre-feet</i>	
October 1895.....	30	71	325	(1)
January 1897.....	30	247-353	730	(2)
October 1898.....	1		162	
October 15-November 30, 1901.....	45		1,377	
March 1904.....	5		810	
1906-07.....	3	2,472	891	(3)
Various.....	Unknown		324	

¹ In 24 hours after the sluice gate was opened a channel extending 1,150 feet above the dam had been formed in the deposits. On the fourth day the channel had lengthened to 4,265 feet, and it had a width as great as 131 feet, and a depth of 46 feet at the dam, gradually diminishing upstream.

² In 5 days after the sluice gate was opened a gully had been cut 1¼ miles long, and up to 197 feet wide, in the sediment deposited in the main channel of the reservoir. Some of the side gullies were nearly 100 feet long. In tributary channels gullies were cut in sediment up to 820 feet long and 98 feet wide.

³ The observed sediment content of the outflow was 84 percent the first day, 70 percent the second day, and 25 percent the third day [by volume?]. The water discharge the fourth day was negligible.

It is estimated that up to 1907, 4,865 acre-feet of sediment had been sluiced out, so that the sediment deposited and remaining in the reservoir, 14,200 acre-feet during the 22 years, 1885-1907, should be increased by that amount to obtain the total sediment output of the drainage area. The river carries an average load of approximately 1 percent of sediment [by volume?] (89).

It was concluded from experiences in 1906-07 that, in order to make sluicing worth while the water discharge should be at least 177 second-feet. Entirely satisfactory results were obtained only when the discharge was in the range of 700 to 1,000 second-feet. The maximum discharge of the river is approximately 28,250 second-feet. Attempts to sluice out sediment from a partly filled reservoir failed completely. It was proposed to build an auxiliary reservoir upstream from Habra Reservoir merely to supply sluicing water at the close of each irrigation season, because a sufficient discharge was seldom available at the time desired.

According to Meyers (89) the Hamiz Reservoir on the Hamiz River in Algeria, built in 1872 [1885? (*132, p. 100*)] with a capacity of 11,340 acre-feet and a drainage area of 54 square miles, had lost 1,215 acre-feet of 10.7 percent of its capacity in the 29 years to 1901. The average sediment content of the inflow is about 0.5 percent. In 1901, systematic sluicing was begun through two circular sluice gates, each having a diameter of 3.77 feet. These gates were left open during the early part of each rainy season from 1901 to 1908. Twenty-three percent of the total water supply was used in sluicing. No part of the sediment deposited prior to 1901 was removed, but further loss of capacity was prevented.

Labelle (80) reports that in 1905 he examined 343 masonry irrigation dams in the province of Cavite, Philippine Islands. These dams, several of which were built about 1880 or earlier, ranged from 10 to 80 feet in height. All that had undersluices were silted to the bottom of the sluice-gate intake, but no higher. Where the intake was blocked, as it was in one case, the dam was silted to the top. Two dams, with small undersluices not exceeding 3 square feet in area, had a good depth of water below the outlet gate as well as a large water surface area, and showed powerful effects of undersluicing.

When Zuni Reservoir near Black Rock, N. Mex., was 80 percent filled with sediment in July 1931, a hole was blasted in the gate tower for the installation of a 4- by 6-foot sluice gate. Between this date and October 15, 1931, when the gate installation was completed, 500 acre-feet were sluiced from the reservoir and by July 1932, 629 acre-feet of sediment had been evacuated. Since then sluicing operations through the gate have continued each year when water was available. The gain in capacity after 1931, shown in figure 17 (p. 39), is the result of these sluicing operations.

According to Cleary (39) the Lower Salt Creek Reservoir in Wyoming was constructed in January 1923 with a capacity of 2,707 acre-feet on a stream that had an annual runoff ranging from 22,000 to 166,000 acre-feet during the period 1923-28. A survey in November 1926 showed that the capacity had been reduced 76 percent. In that year a temporary structure was placed on top of the spillway, raising its elevation 3 feet. By 1928, however, only 200 acre-feet of storage was left even at this higher elevation, and by the end of 1932 storage

had decreased to 78 acre-feet. This condition led to construction in January 1933 of two motor-driven, roller-bearing 8- by 12-foot sluice gates having a combined discharge capacity of about 6,000 second-feet. Construction was completed by the middle of April. By June 1, 1933, sluicing had increased the available capacity to 378 acre-feet, and on August 25, 1933, a careful survey indicated a capacity of 918 acre-feet had been obtained by the flushing action of floods through these two gates. Surveys in the summer of 1935 showed a capacity of 1,300 acre-feet or very nearly one-half of the original capacity.²⁰

The Folsom Dam on the American River 8 miles north of Folsom, Calif., was originally built in 1891 to a height of 69.5 feet above stream-bed level for irrigation and water power. In the center of the dam on a level with the low-water flow of the river three 4- by 4-foot undersluices were installed. As the American River was known to carry a large amount of sediment in suspension during floods, it was expected that these sluices, operating under a 60-foot head, would satisfactorily flush out the sediment deposits. It was found, however, that their effect was extremely local, that only a small channel-way was scoured out in front of them (135, p. 214). The area of these undersluices was found to be entirely too small in comparison to the flood discharge. Water depths of 31 feet over the spillway and a deposition of 30 feet of "wet silt" by one spring flood were reported.

An anonymous article (8) describes the construction of sluice gates in a concrete dam built for irrigation storage on the Bear River, 7 miles east of Wheatland, Calif., in the late 1920's. This dam is a gravity-arch structure, 76 feet in maximum height, with a crest length of 376 feet, creating a reservoir of approximately 3,400 acre-feet, and receiving drainage from 262 square miles, from which the estimated maximum discharge is 24,000 second-feet. In order to pass the large amount of gravel and sand transported by the Bear River, six 7- by 12-foot sluiceways were built into the lower part of the spillway section. The upstream end of each sluiceway is provided with steel sliding gates. The vertical distance from the top of the central sluiceway to the spillway crest is 29 feet. The gates are operated by a hoist car traveling on a track above the wasteway crest. Sluiceway floors have a grade of 2 percent and are lined with timber to facilitate renewal. Storage is needed in this project only in the latter part of the irrigation season, as the district has normal flow rights in the river, which are ample during the first part of the season. When the spring floods have abated, the sluicing gates are closed.

Appraisal.—Orth (95, p. 353) has given perhaps the most succinct statement concerning the factors favoring flood sluicing, or flushing, as he terms it:

Flushings are the more efficient:

1. The less the depth of stored water at flushing.
2. The greater the discharge of the flushing stream.
3. The greater the dimensions of the flushing outlet.
4. The lower the location of the outlet.
5. The more favorable the location of outlet.
6. The longer the flushing lasts.
7. The narrower the reservoir (steep banks).
8. The steeper the original stream gradient through the reservoir.
9. The shorter the reservoir.

²⁰ In correspondence from J. B. CLEARY to Soil Conservation Service, Jan. 15, 1937.

10. The straighter the reservoir.
11. The more advanced the silting.
12. The finer the particles of the sediment.
13. The rounder the individual particles of sediment.
14. The younger and the less consolidated the sediment.

Davis (42) in 1897 concluded that sluicing by the Spanish method will clean out only a small area extending on a steep grade, for a moderate distance above the scouring sluices. This conclusion appears to be substantially correct for the western irrigation reservoirs of the broad-basin type that Davis was discussing.

Wilson (136) held the opinion that sluice gates have little effect unless the area of the openings is great. In other words, he advocates sluice gates like those of the Bhatgarh and Aswan Dams for rapidly discharging flood flows and preventing sedimentation in preference to gates for sluicing existing deposits. He cites the failure of small gates to prevent silting at Lake Fife, at Vir, and other places in India. Put another way, he considers that if the dam is high and the discharge of the undersluices will keep the water level below the spillway elevation at flood stage, then they will be efficient. If the dam is low and the sluices will not keep the water level below spillway elevation, they will have little effect.

Lewis (84) notes that coarse material can be moved, after it has deposited in the reservoir, only by high velocities, and that to create such velocities would necessitate the maintenance of a low water level in the reservoirs (in South Africa) by passing all floods in, say, 1 year out of every 4 years. The irrigators of that region have protested against trying out such methods because, having passed water for scouring, they would risk lack of flood runoff for such a long period that crops would suffer. Even if successful in scouring out appreciable volumes of sediment, the water during that year, charged with deposits of 3 years, might be quite unusable. The scouring of sands from the upper end of the reservoir, however, will promote the scouring of finer sediment in the lower end of the reservoir. Such sluicing methods may have to be tried in South Africa, Lewis believes, when the cost of raising dams becomes prohibitive.

Schoklitsch (107, p. 72) in discussing sluicing in power reservoirs, points out that the process—

is the most effective during the first hours. Later on, the effect decreases rapidly and it is therefore impractical to interrupt the operation of a power plant for a longer period for the purpose of flushing the region above the dam. In order to keep the area, upstream from the dam, free from silt accumulation, it is more practical to have frequent short flushings, instead of long-lasting ones. A flushing of silt at the original backwater limit is obviously impossible, considering the time available for flushings. It is impossible to flush the silt, while sustaining the reservoir surface-level, as model-experiments and experience have taught. It is evident from a model-experiment * * * that if flushing takes place under a sustained water level, only a very limited area is cleared, the dimensions of which are totally negligible when it comes to keeping a reservoir free of silt.

Finally, * * * flushing of a reservoir nearly always leads to complaints of owners of land below the dam, and from lease holders of fisheries. During the flushing process, extreme quantities of suspended matter are stirred up and carried in suspension down the river over long stretches. For the most part, these are again deposited in the next reservoir, as a rule compelling the inhabitants of the lower regions soon, likewise, to flush the reservoir. Moreover, the great quantities of suspended matter clog up the gills of the fish, which often die in great number.

It appears that, in this country, flood scouring through undersluices could be used chiefly in (1) small power dams that depend to an important extent on pondage, but not on storage, (2) smaller irrigation reservoirs on streams where the flow is highly seasonable or erratic and where only a small fraction of the total annual flow can be stored as a result of physical conditions or conflicting water rights, (3) water-supply reservoirs that are a unit in an interconnected system of reservoirs, so that the gates in a particular dam might be opened and the reservoir scoured while other sources supply water needs, (4) navigation reservoirs where undersluices might be used in fixed crest dams as an alternative to the wicket-type navigation dams such as those on the Ohio River, and (5) any reservoirs in narrow channels, gorges, or canyons where water wastage can be afforded.

Large undersluices equipped with power-controlled gates will add materially to the cost of a dam; but for the type of reservoir in which flood sluicing will be really effective, the cost would probably be justified.

SLUICING WITH CONTROLLED WATER

Sluicing with controlled water differs from flood sluicing in that the controlled water supply permits choosing the time of sluicing more advantageously and that the water may be directed more effectively against the sediment deposits. Whereas flood sluicing depends either on the generally fortuitous occurrence of a flood, or on being able to release rapidly all of a full or nearly full supply of water in the main reservoir, sluicing with controlled water is done when the main reservoir is empty. The water available from diversion or supplementary reservoirs is under control and may be so released or directed against the deposits in the main reservoir that the amount of sluicing accomplished per unit of available water is increased.

As early as 1897, Davis (*42*, p. 82) outlined a method of sluicing with controlled water for the maintenance of capacity in proposed reservoirs on the Gila and Salt Rivers, Ariz. Modifications of this plan for reservoirs on the Gila were discussed at length by Newell in the first and third annual reports of the Reclamation Service (*129*, pp. 83-85; *130*, pp. 417-418); and Davis and Wilson (*43*, pp. 377-379) recommended a similar plan for solution of the sedimentation problem in Elephant Butte Reservoir on the Rio Grande. So far as the writer knows, none of these plans has been used at any large reservoir in this country, although sluicing of equalizing storage reservoirs of municipal waterworks systems is common.

In the plans of Davis and Newell, controllable water was to be obtained either by diverting or constructing a supplementary storage dam, higher up on the main stream or on a tributary at a point well above the spillway level of the main reservoir. In the plan for Elephant Butte Reservoir, it was proposed that one of several sites providing storage of several hundred thousand acre-feet should be developed.

In the Gila and Salt River plans, water was to be conveyed from the auxiliary diversion or storage dam through one or more pipes, flumes, or canals around the upper edge of the main reservoir above its high-water line to the vicinity of the dam. In the Elephant Butte scheme, water was simply to be released with large discharge into the main stream channel to augment the natural flow when desired.

In Davis' original plan, which envisioned a pipe line around the reservoir, hydraulic giants for sluicing in the bottom of the main reservoir were to be connected to the line at topographically favorable spots, such as ridges jutting into the lake. Another plan involving a high-line canal provided controlled openings at similar locations through which water could be released to rush down the reservoir side slopes and scour out sediment by "ground sluicing." All engineers admitted, however, that hydraulic giants would be needed to remove compacted fine sediments over large areas.

The main reservoir dam was to be equipped with one or more large outlet tunnels, or tunnels were to be driven through bedrock around the dam near the elevation of its base. In a plan for San Carlos Reservoir two tunnels, 10 by 13 feet in diameter, were to be developed in bedrock around each end of the dam. The tunnels would be controlled by gates, and, in order to keep their entrances free of sediment, would be opened at times when water began to go over the spillway, as well as when all water from the reservoir had been withdrawn for use and the controlled supply was being used for sluicing. It was believed by most early writers that use of the sediment-laden water downstream would be beneficial rather than detrimental to irrigators because of the fertilizing value of the fine sediment.

One of the advantages claimed for this method of sluicing was that a deep channel would be cut in the lower part of the reservoir, increasing the capacity in the deeper parts of the lake and increasing the ratio of storage to surface area of water, thereby decreasing evaporation losses.

Davis estimated that 20 percent of the expected 8,000 acre-feet of annual sediment inflow to San Carlos Reservoir could be removed by this sluicing practice. Newell estimated (130, pp. 417-418) that the proposed El Paso Reservoir on the Gila River would accumulate 7,107 acre-feet of sediment annually, and would lose 60 percent of its capacity in 46 years, at which time the mud would be 46 feet deep in the channel just above the dam, decreasing in thickness to zero 13½ miles upstream. By ground sluicing, without the use of hydraulic monitors, he estimated a channel 50 feet wide at the bottom, with 4 to 1 slopes, would be cut through these deposits to the original bed level. He calculated the volume of such a channel to be 6,428 acre-feet, or less than 1 year's accumulation.

In contrast, Newell estimated that in the proposed Engle Reservoir on the Gila River, which was expected to lose 60 percent of its capacity in 82 years, a channel 30 miles long would be cut to the same width and slopes but with a depth of 150 feet at the dam. Whereas the annual silting rate was estimated to be 14,580 acre-feet in this reservoir, the volume of sediment sluiced out to form such a channel was estimated to be 120,613 acre-feet or the accumulation of 8¼ years.

In the Elephant Butte plan the augmented natural flow of the river was expected by Davis and Wilson to cut a channel 50 miles long, up to 240 feet deep at the dam, 250 feet wide at the base, and having 3 to 1 side slopes, representing a total volume of more than 500,000 acre-feet. The water flowing out of the reservoir was expected to carry 10 to 15 percent solids.

Edgecombe (47, pp. 5-6), in commenting on this proposal, notes that although Davis and Wilson did not state their method of arriving

at a channel width of 250 feet, the estimated discharge required, nor the time needed for such a sluicing operation, it would actually require $3\frac{1}{3}$ million acre-feet of water to clear out 500,000 acre-feet of sediment in 1 year, and this is about 3 times the mean annual discharge of the Rio Grande at the head of the reservoir.

Davis admitted that his scheme would be expensive, but claimed that the cost would be offset by its effectiveness. Newell estimated that removal of sediment by "ground sluicing" could be accomplished at a cost of 8 to 9 mills per cubic yard, and that the supplementary use of hydraulic monitors would result in a cost of only about 1 cent per cubic yard (\$16 per acre-foot).

The Board of Army Engineers, considering the San Carlos project (123, p. 43), raised objections to Davis' sluicing scheme as follows: (1) The San Carlos Reservoir must be large enough to hold over storage during a series of low-flow years. Therefore the reservoir would seldom be empty, or if nearly empty the use of remaining water and the flow of the stream for sluicing would leave the reservoir without stored water for the next irrigation season. (2) Because of the nature of the topography around the reservoir, it would be financially infeasible to construct a high-line canal.

One of the most recent sluicing operations in this country has been the cleaning of the Upper San Fernando Reservoir of the Los Angeles, Calif., water-supply system (14). Although most of the water entering this reservoir is supplied by the Owens Valley aqueduct, there is a natural drainage area of 5,430 acres, of which about 20 percent is cultivated, and 80 percent is in brush. Sediment derived from this area during the period 1921-39 reduced the reservoir's capacity from 1,977 acre-feet to about 1,500 acre-feet. Much of the silting was the result of the flood of March 1938.

In 1939 the reservoir was drained. A flow of about 10 second-feet was let into the reservoir from the aqueduct at the upper end, and this cut a meandering channel through the basin. To aid removal, an 8-inch pipe, 1,100 feet long, was used to bring a high-pressure water supply to hose lines $2\frac{1}{4}$ and 4 inches in diameter equipped with $\frac{3}{4}$ -inch and $1\frac{1}{2}$ -inch nozzles. Three men were required to handle the large nozzle and two men to handle the smaller one.

Of the 20-foot thickness of sediment in the lower part of the reservoir, the upper 5 feet was very soft and would assume an angle of repose of about 10° when channels were cut through it. The bottom 15 feet, a very dense clayey material, would stand in a vertical face without disintegrating.

The reservoir was kept unwatered 38 days, and an estimated 20,000 cubic yards (12.4 acre-feet) of sediment was sluiced through a 62-inch concrete pipe running 600 feet on a 1-percent grade from the outlet tower, and was discharged through blow-off gates of 12-inch, 24-inch, and 30-inch diameter. Sluicing was used especially to clear the areas around the outlet tower, and to increase the concentration of solids in the outflow.

Upper San Fernando Reservoir is immediately above Lower San Fernando Reservoir. In the extreme upper end of the lower reservoir an earth-fill dam containing some 17,000 cubic yards and having a length of 450 feet was constructed to impound 20,000 cubic yards of sediment on a 1-percent slope. When this amount was deposited, sluicing operations were stopped.

A total of 220 man-days of time was expended in the sluicing operations, with the result of removing 90 cubic yards per man-day. Sluicing alone, however, is considered to have accounted for only 50 cubic yards per man-day, the remainder being the result of draining. All of the sediment removal, however, was effected because a supplementary water supply was available.

An entirely different plan of sluicing with controlled water was suggested by Hughes (*123, p. 151*). This method consists of (1) one or more conduits extending from the base of the dam along the floor of the reservoir; (2) manholes, or standpipes of various height, built into the conduits with proper spacing over the area to be sluiced; (3) vertical pipes capable of being revolved in their supporting bearings, and projecting downward from the water surface into the fixed standpipes or manholes to a considerable depth; (4) horizontal pipes of adjustable length supported by pontoons connected by right-angle elbows with the vertical pipes; and (5) movable inclined suction pipes, extending from the sediment below to the water surface and flexibly connected there with the horizontal pipes.

Jet pipes would extend down the suction pipes to provide a pressure method of loosening compacted sediment, and a vacuum pump would be installed at the elbow over the standpipe to exhaust air in the system. The suction end of the pipe would revolve in circles around the standpipe by shortening and lengthening the horizontal arm to a maximum of one-half to three-quarters of a mile. The pipes could be transferred by boat from one standpipe to another.

Hughes considered the scheme impracticable for San Carlos Reservoir, because of (1) high installation cost and the long period of idleness before the apparatus was needed, during which time deterioration by floods, leakage, and filling up with sediment might be expected; (2) the great strength required in the standpipes, because of high winds, which would result in a large cost; (3) the insufficiency of siphonage power with long pipe lines. Hughes calculated that the theoretical limit of suction in the siphon with a complete vacuum would be 13.4 pounds per square inch at the elevation of San Carlos but notes that river and harbor dredging pipe lines one-half mile long require a vacuum of 10 to 15 inches of mercury on the suction, equivalent to 5 to $7\frac{1}{2}$ pounds per square inch, and nearly 25 pounds per square inch more on the discharge, making a total of over 30 pounds per square inch, thus indicating the inadequacy of siphonage alone in this scheme.

Bonnet (*26, pp. 404-406*) proposed a somewhat similar plan involving a network of tubes over the bottom of the reservoir leading to an outlet in the dam. The main tube, of cast iron or concrete, approximately 59 inches in diameter, extending up the thalweg of the reservoir, would have many side tubes about 29 inches in diameter, which would be perforated with openings. Chains for opening the inlets would extend to the water surface, where they would be attached to buoys and could be reached by boat. There would be two smaller openings in the cover plate of each large opening for freeing the inlet cover of sediment accumulated on them. Bonnet admits the system would be initially expensive, but claims its operation would be cheap. The amount of water required, however, for effective flushing would doubtless be large. Orth (*95, p. 355*) considers this system inferior to that of a flexible pipe line and suction dredge (see p. 89).

Appraisal.—The advantages of sluicing with a controlled water supply are: (1) Sluicing can be timed advantageously with respect to availability of water and water demand, and (2) generally, more sediment can be removed per unit of water used than in flood scouring or draining and flushing.

The principal objections to these methods are: (1) the large initial cost of the necessary installations compares unfavorably with the cost of other plans, particularly with development of additional storage, so long as suitable sites for large reservoirs are still available, (2) there are several limitations on the physical feasibility of these methods, and (3) the effects of rapid sluicing may be injurious to the channel below the reservoir, or to downstream reservoirs.

If effective scouring were to be obtained by release of water into the main channel from upstream reservoirs, the auxiliary dams either would need to be equipped with large gates that could release water rapidly enough to produce sharp peak flows, or they would have to impound sufficient water to supply a sustained flow for weeks. In arid regions these flows of relatively clear water would entrain much sediment in the reaches between the subsidiary reservoir and the main storage basin. Hence, scouring out the fine sediment would be partly offset by the inevitable deposition of coarser material transported into the basin. Furthermore, long sustained flows through the reservoir would result in a large wastage of water, unless they could be produced at a time when the water, even though heavily charged with silt and clay, could be utilized for irrigation or other purposes below the dam.

It is conceivable that these plans might be used advantageously in some power systems. For example, Saville (105, p. 27) has suggested that if one or more high storage dams were constructed on the headwaters of Deep River, N. C., and were equipped with large gates, flows just within channel capacity could be developed. These flows would be effective in scouring out deposits behind the lower dams of the river if the dams were equipped with suitable gates. As the power plants at these smaller dams normally do not operate at night, or over the week end, there would be ample time for scouring.

The proposals for sluicing fine-textured, poorly compacted sediment through a network of pipes from the lower part of the reservoir to the dam would seem to merit further investigation. Admittedly the installation of such equipment would be costly, but such a system might be useful, not only in removing the sediment that settles normally from suspension, before it has a chance to become so compact that its removal becomes difficult, but also in picking up and venting density currents.

SLUICING WITH HYDRAULIC AND MECHANICAL AGITATION

Any methods that stir up, break up, or move deposits of sediment into a stream current flowing through a drained reservoir basin or into a lake current moving through and out of a full reservoir will tend to make the removal of sediment from the reservoir more complete.

An important feature of Davis' scheme of sluicing with controlled water described in the preceding section was the installation of hydraulic monitors that could be directed at the beds of sediment. Lippincott (85), in his proposal for diversion of water in canals around impounding reservoirs (see pp. 58-59), suggested that water skimmed

over the top of the canal, or at least the water head in the canal, would permit the use of hydraulic monitors for sluicing sediment.

Jarvis, in discussing a paper by Robinson (102), concluded that the minimum cost of excavating sediment, estimated to be \$160 per acre-foot, would be prohibitive, and that the only useful method to accomplish this purpose would be some adaptation of hydraulic sluicing. Using various assumptions, he estimated the cost of sediment removal by this method would be \$40 per acre-foot. The lowest costs, he believed, would result from proper manipulation of outlet gates, which should be of ample dimensions, together with the judicious use of jets from hydraulic giants mounted on a barge for use around the edges of the reservoir during the irrigation season.

Heinly (68) described sluicing in Buena Vista Reservoir, a part of the water-supply system of Los Angeles, Calif. The original capacity of this storage basin was 39.9 acre-feet. Its main water supply comes through a diversion conduit, but it has a natural drainage area of 19.2 acres. When emptied in January 1910, for the first time in 15 years, sediment deposits were found to be several feet thick. The deposits were stirred up and made into a "soil saturated solution" by hydraulic jets playing upon them so that they would flow to the outlet in the dam.

Calmels (37) described a method of agitating reservoir sediment by blowing air into it and thus causing it to move to the dam in greater concentration in the water released. This practice was tried experimentally in the reservoir at St. Denis du Sig, Oran Province, Algeria. This dam, although equipped with flood sluice gates, which were used regularly, had lost 567 acre-feet of its original capacity of 2,837 acre-feet by 1879.

In the small-scale experiments, a 12-horsepower steam engine was attached to a compressed-air generator and a pressure accumulator. From the pressure accumulator a 1½-inch iron pipe, tightly sealed at the joints, was run to a barge, where it was connected by rubber hose to a nozzle that forced air into the sediment (fig. 44). Calmels proposed that, in a large-scale operation, water released through the dam under head should be used to drive a turbine-air compressor located

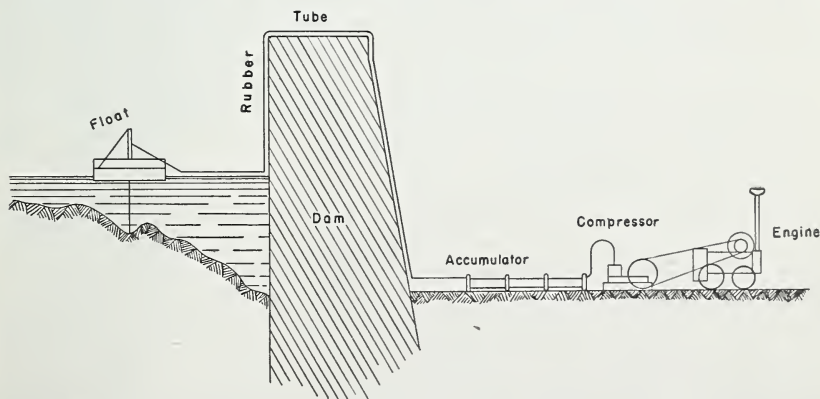


FIGURE 44.—Plan of siphon dredging with agitation of the sediment by compressed air. (After Calmels.)

below the dam. Iron pipe and rubber hose would convey air over the dam to a pontoon consisting of two "floating caissons" connected by a bridge spanning an opening of about $2\frac{1}{2}$ feet. Over this opening a pulley suspended from a cross beam held by vertical supports about $5\frac{1}{2}$ feet above the pontoon, would be used to raise and lower the nozzle. Two nozzles were designed. The first of these was 4.17 feet long, 0.15 foot in inside diameter, and terminated in a cone having an angle of 12° to the axis of the nozzle. The cone was perforated with 6 openings 0.008 foot in diameter. This nozzle could be used for high-pressure work—5 to 6 atmospheres. A second nozzle has only one opening 0.038 foot in diameter and was designed for use continuously at 2 to $2\frac{1}{2}$ atmospheres.

In a sluicing operation the nozzle was to be used first against the upstream face of the dam to develop a hole in the deposits around the outlet. In Calmels' opinion, slumping, sliding, and flowage of material into this hole would occur so readily (probably by induced density currents) that he considered it unlikely that the apparatus would have to be operated very far above the dam. His tests showed that water became turbid for a distance of about 100 feet around the nozzle in a few minutes, and that the stirred-up sediment ran off even when it constituted $1\frac{1}{2}$ times its water volume. At the surface of the reservoir it was found that the nozzle had produced a concentration of 14 percent [by weight?] of sediment in the water.

Calmels estimated that an apparatus for cleaning a reservoir with a capacity of about 10,000 acre-feet would cost about \$12,600.

Nagle (92, p. 45) reported a novel method used in the Lozoya Reservoir, built about 1855 on the Rio Lozoya, to supplement the water supply of Madrid, Spain. A large disk wheel that revolved horizontally and could be raised or lowered was attached to a large flat boat. To the face of this wheel narrow wings or teeth were attached, and these beat the sediment into fine mud, which could be moved by a small current. The steam engine that propelled the boat also drove the wheel. The apparatus was reported to do good work whenever there was a considerable amount of water flowing through the reservoir. It wasted no water, and could be used when desired.

Blasting sediment deposits in time of flood has been considered by several engineers. Saville (105, p. 26) states that the problem was taken up with powder manufacturers, but the prevailing opinion was that blasting would prove more expensive than alternative methods.

A number of methods similar to the ones described have been used in cleaning sediment from water-storage basins of municipal and corporate water systems.

Appraisal.—Most authors, who have considered methods of agitating and sluicing sediment, were of the opinion that they were unsatisfactory. Edgecombe (47, p. 19) states that "Stirring up the silt deposit with a jet, and allowing it to pass out with the water drawn off, has been suggested as a method, but it does not appear to work satisfactorily." He notes that a new reservoir could have been constructed for the cost (\$75.80 per acre-foot) of cleaning out two small, brick-lined storage reservoirs at Cincinnati, Ohio, whose combined capacity, according to Ellms (49) who described the cleaning, was approximately 1,200 acre-feet.

Hemphill (69, p. 1070) states that the method involving "stirring up the silt with a jet, and allowing it to pass out with water drawn

off * * * does not work satisfactorily even in the smallest reservoirs."

The writer believes that further investigation is needed before the usefulness of schemes for agitating sediment should be discounted. Even with the meager present knowledge of density currents, it would appear that they might be created, or at least aided, by agitating already deposited sediment. Often, equipment already available to reservoir owners, such as pumping units or air compressors and hose lines, mounted on a substantial barge, could be rigged up to supply a powerful water or air jet to be directed against the bottom deposits. At comparatively nominal cost, considerable quantities of fine sediment might be moved in subsurface currents toward outlets in the dam.

In power reservoirs that have a large dead storage space, any methods that would tend to cause sediment to move from the useful storage zone in the upper part of the reservoir to the dead storage zone in the lower end would be useful for a time in maintaining the available pondage or storage.

Wherever draining, flushing, or sluicing appear to be warranted, the additional use of mechanical or hydraulic means for stirring up the sediment deposits or sloughing them off into a stream flowing through the reservoir basin should be considered.

WATERSHED EROSION CONTROL

Watershed erosion control embraces all those measures that are effective in preventing or delaying the movement of soil and rock particles from their points of origin in the drainage area to the reservoir. Fundamentally, watershed erosion control differs from all other methods of reservoir silting control in that it aims at eliminating the problem at its source by preventing the formation of sediment.

The scope of watershed erosion control is as broad as the fields of soil conservation, forestry, and land utilization. On these subjects hundreds of books and articles have been written in America and abroad since the beginning of the century. For a comprehensive treatment of all aspects of soil conservation the reader should consult the authoritative work of Bennett (22); of forestry, "A National Plan for American Forestry" (126); and of range problems, "The Western Range" (127).

As shown in these and other publications (125, 128), it has been so convincingly demonstrated by experiment and practice that conservation measures are effective in reducing the rate of soil loss from the land that it may be assumed that erosion-control measures on the drainage area of any reservoir are desirable,²¹ and that for the purposes

²¹ Objection has been raised in some of the arid States to conservation measures on the grounds that they decrease the supply of water reaching storage reservoirs. It has been claimed that additional vegetation would increase transpiration and evaporation, and that small structures would pond or spread water and increase evaporation and percolation. Proponents of watershed control have countered with the argument that conservation measures would reduce the sediment and dissolved salts carried by runoff and assure a more uniform stream flow, thereby actually increasing the net yield of usable water over a period of years. It is possible that the circumstances in one drainage area would favor the first point of view, and in another the latter. In any event, it has been clearly shown by recent studies in several of the major drainage basins of the West, namely, the Colorado, Gila, and Rio Grande, that less than half the area of these basins contributes more than three-fourths of the sediment, but less than one-fourth of the water. It would seem to be sound national policy, aimed at the preservation of vital water storage sites, to forego the use of 5 or 10 percent of the runoff of a drainage basin, if necessary, to achieve a reduction of possibly 50 percent or more in the sediment load brought into major reservoirs.

of this publication the questions of particular moment are: (1) What specific measures can be used and what are their effects; (2) how may programs of erosion control be developed; and (3) what costs are involved in such programs.

In this publication, watershed erosion control is considered with respect to (1) the sources of sediment affecting reservoirs, and why they should be determined; (2) the effects of man's use of the land on increasing rates of sediment production; (3) the methods of controlling sediment production; (4) examples of efforts to protect reservoir watershed; and (5) plans for achieving erosion control, which represents an appraisal.

SOURCES OF SEDIMENT

Historical evidence indicates that in most drainage basins of the United States, erosion and the sediment loads of streams have increased greatly since the country was settled by white men. The discussion here centers on these sources of increased or accelerated sediment production rather than on those areas where the geologic norm of erosion is high, as in the badlands of the Dakotas, the Bryce Canyon, Utah, region, the Chinlee badlands of Arizona, or the breaks of the Missouri River. In the main, the aim of erosion control is to reduce the rate of sediment production, to make it as nearly conformable as practicable, under required conditions of land use, to rates prevailing under the geologic norm. Where the effects of sediment are very adverse, and where the geologic norm has always been high, it is not unreasonable, however, to aim at reducing the rate even below this norm.

The first step in watershed control directed toward reservoir protection is to trace the sediment to its points of origin in the drainage basin, and to determine the approximate quantitative yield of each of the principal sediment sources. A map showing the relative degree of accelerated erosion in different parts of the drainage area, while helpful, does not provide the needed quantitative data. It is obvious with only a little study of the landscape that sediment produced by many areas of very rapid erosion is deposited largely on fans and flood plains without ever reaching the main stream channels, whereas other areas of rather inconspicuous erosion adjacent to channels may be quantitatively important sources of reservoir sediment. Sediment sources should be determined, first, with respect to their geographic distribution within the drainage area and, second, with respect to causes or types of production.

The principal types of sediment production are as follows: (1) Sheet erosion by surface runoff, sheet erosion being defined as the removal of surface soil by overland flow without the formation of channels of sufficient depth to impede cultivation; (2) gullying, or the cutting of channels in soil by concentrated runoff; (3) road and railroad erosion, or the washing away of material from cuts, fills, and surfaces of lines of transportation; (4) stream-channel erosion, or the scouring of material by concentrated flow from the beds and banks of streams located in well-defined valleys; (5) flood erosion, or the removal of surface soil by flood flows sweeping across flood plains; (6) erosion incident to construction activities, such as excavation for buildings, bridges, or airports; (7) mining and industrial

wastes dumped into streams or left in positions favorable for erosion.

In contrast with the extensive knowledge of the distribution of erosion, quantitative data on the sources of sediment in specific watersheds are not plentiful. In recent research studies of the Soil Conservation Service, under the writer's supervision, an attempt has been made to develop a survey technique for determining within usable limits of accuracy the sources of sediment in the drainage areas of certain typical reservoirs.

In such a survey of the 6.74-square-mile drainage area above the Lexington City Reservoir, Lexington, N. C., it was found that during the period of accelerated erosion, approximately 200 years, 38.2 percent of the total sediment output of the drainage area had been derived solely from sheet erosion; 37.2 percent had come from land on which both sheet and gully erosion had been active; and 16.7 percent from land completely destroyed by gullying, although such land constitutes only 1.7 percent of the drainage area. Linear gullies large enough to map separately contributed 5.9 percent of the sediment. The remaining 2 percent came from roads. Stream-bank erosion contributed only a negligible quantity of material in this area. Of the total material washed from slopes, 37.7 percent had been deposited in colluvial areas and in the alluvial valleys, whereas 62.3 percent had been transported out of the drainage area, or, since 1935, deposited in the city reservoir. This survey has also shown the percentages of sediment derived from each of the natural drainage subdivisions of the area.

Studies made as part of a flood-control survey by the United States Department of Agriculture in the Little Tallahatchie River drainage area of 1,509 square miles in northern Mississippi have shown large differences in the amounts of sediment produced by different physiographic subdivisions of the area. It was estimated on the basis of erosion and sedimentation surveys, that for the drainage area as a whole 18 percent of the sediment is coming from usable agricultural land and woodland, 77 percent from land abandoned because of erosion and nonagricultural land, and 5 percent from roads. The greatest contrast was found between the sources of sediment in the Brown Loam area, a belt of loessal soils, underlain at depths of a few feet by the highly erodible Holly Springs Sand (Eocene Wilcox age), and the Flatwoods area underlain by clays (Eocene Midway age). In the Brown Loam area, only 11 percent of the sediment came from usable agricultural land and woodland, whereas 86 percent came from abandoned and nonagricultural land and 3 percent from roads. In the Flatwoods area, on the other hand, 62 percent came from usable land, 27 percent from abandoned and nonagricultural land, and 11 percent from roads. The other two subdivisions of the drainage area, the Clay Hills and the Pontotoc Ridge, were found to be intermediate between these extremes, except that the Clay Hills showed a slightly higher contribution from roads.

In a study of the contribution by gullies to stream loads, it was estimated that entrenched channels led from 63 percent of the gullies in the Brown Loam area to main stream channels and, hence, provided sluiceways for delivering the sediment output of these gullies directly to points where the material could be carried downstream. On the other hand, 37 percent of the gullies had no channels, and their

sediment output was deposited on alluvial fans at their mouths; thus these gullies contribute little except the finest material to downstream flows. In planning an erosion-control program to reduce reservoir silting in such an area, it would obviously be of importance to control first those gullies that are feeding sediment directly to the main streams.

In a flood-control survey by the Department of Agriculture of the 437-square mile drainage area of Buffalo Creek, which empties into the harbor at Buffalo, N. Y., it was found that the principal source of sediment was stream-bank erosion. Based on surveys of 1-mile reaches of the principal stream channels, separated by 5-mile gaps, and on a conservation survey of the drainage area, it was estimated that approximately 80 percent of the total material reaching Buffalo harbor is derived from the stream banks, whereas 20 percent comes from erosion of the land surface.

In a similar flood-control survey of the sources of sediment reaching Elephant Butte Reservoir on the Rio Grande, N. Mex., it was estimated from erosion and sedimentation surveys that of the 18,034 acre-feet deposited annually (1915-35), 9,700 acre-feet, or 54-percent, was derived from the Rio Puerco, a tributary that drains an area of 6,100 square miles, or only 23 percent of the total drainage area. It was further estimated that of the annual sediment output of the Rio Puerco, approximately 40 percent is derived from bank erosion along the main Rio Puerco channel, another 30 percent is derived from erosion and head cutting of tributary arroyos, and 30 percent is derived from erosion on slopes of the drainage area.

In a recent detailed study of two small areas in the Little Sioux drainage basin in northwestern Iowa, Mortimore (90), found that from one watershed of 114 acres about 3 miles northwest of Correctionville, Iowa, the soil loss since the beginning of accelerated erosion had been 71.7 acre-feet, of which 22.0 acre-feet were derived from gully and roadside erosion, and 49.7 acre-feet from sheet erosion. All but 1.9 acre-feet of this eroded soil was found to have been deposited in an alluvial fan at the mouth of the drainage area, and in small patches within the watershed.

Suspended-load records obtained by the United States Geological Survey at several stations in the Colorado River drainage basin have been used by Stabler (113, pp. 277-284) to estimate the percentages of sediment derived from major subdivisions of this basin.

In a recent article the writer (30) has pointed out that soil losses from slopes as measured on experimental plots may differ widely from losses from complete drainage areas, as a result of deposition on slopes and flood plains and erosion of channels. Figure 45, based on data obtained from an unpublished report by Hoyt,²² shows that 5 plots of 2 to 3¼ acres under different land use treatment at the Clarinda, Iowa, Conservation Experiment Station during 25 periods of surface runoff from June 1934 to September 1938 had total soil losses ranging from 0.44 to 8.3 tons per acre. During the same periods of runoff, the suspended-sediment load of the East and West Tarkio Creek drainage areas, within which the station is located, averaged

²² HOYT, W. G. RAINFALL-RUNOFF RELATIONS EAST AND WEST TARKIO CREEKS, IOWA AND MISSOURI, AND COMPARISON OF SURFACE RUNOFF, SILT LOSS, DIRECT RUNOFF, AND SUSPENDED MATTER, TARKIO CREEK AREA AND LA CROSSE, WISCONSIN, AREA. U. S. Geol. Survey. 1940. [Unpublished.]

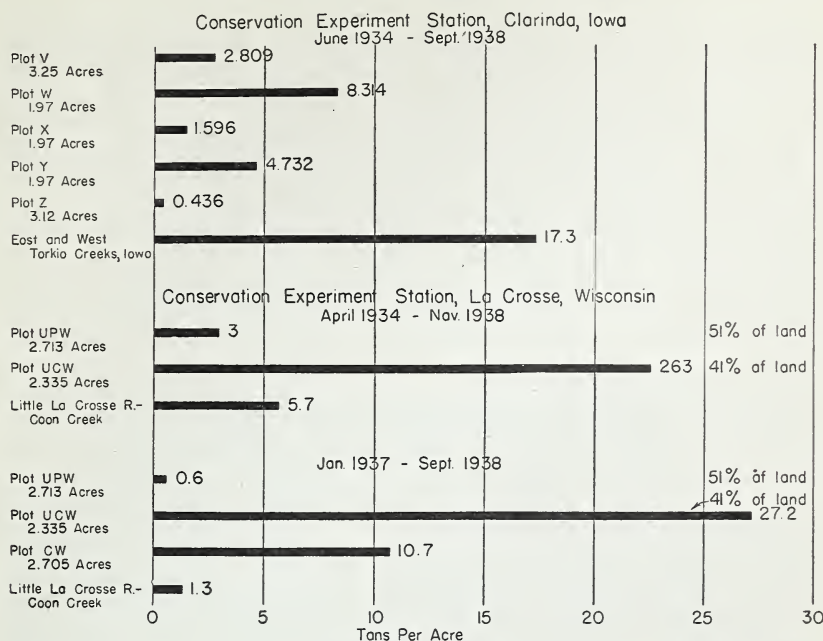


FIGURE 45.—Comparison of soil losses from experiment plots and the sediment load of streams draining adjacent watersheds.

17.3 tons per acre. In fact, during 32 storms the plots showed no soil loss, but during these storms the streams transported 672,000 tons of material out of the drainage areas. On the other hand, soil losses on watershed plots of 2 to 3 acres at the La Crosse, Wis., Conservation Experiment Station, during 116 periods of runoff from April 1934 to November 1938, ranged from 3 tons per acre for untterraced pasture to 263 tons per acre for cultivated land. For the same periods of runoff the adjacent Coon Creek and Little La Crosse River carried a suspended load of 5.7 tons per acre, far below an average based on application of plot measurements in proportion to land use in their drainage areas.

Where such data show that erosion losses are less than the stream load, this implies that there are important sources of erosional debris other than the farm land sampled by the plots. Study of the Tarkio Creek area discloses that stream-bank erosion can account for the excess of sediment load. Where stream load is only a fraction of erosion measured on the land, it is obvious that large quantities of eroded material must be stopping on gentler slopes and flood plains. Measurements in Coon Creek Valley have disclosed that between 4,500 and 5,000 acre-feet of sediment has been deposited in it since accelerated erosion began, and this does not include large additional amounts in tributary valleys and upland swales.

There is an erroneous notion prevalent among reservoir owners and operators that much of the sedimentation in lakes results from wave erosion along the shore line. In a study of silting in Lake Decatur, Decatur, Ill. (62), it was found that erosion of the shore line, espe-

cially conspicuous at this lake, had accounted for only about 1 percent of the total material deposited in the reservoir. In Lake Dallas, near Dallas, Tex., the principal wave-cut areas had contributed only 79 acre-feet out of 13,687 acre-feet of sediment measured in the lake in 1938. Including unmeasured areas, the total contributed by wave erosion was undoubtedly less than 1 percent. Studies of other lakes have indicated that the amount contributed by shore-line erosion is almost always less than 5 percent of the total sediment.

Frank (55) states that studies in the San Francisco peninsular region of hilly terrain have shown that the major cause of reservoir sedimentation is the serious erosion resulting from sliding and slumping from State and county highways. Much of the sediment production from some watersheds along the steep San Gabriel Mountain front near Los Angeles also has been attributed to construction of highways. Johnson and Brown (75) state that in a recent survey of the drainage area of Lake Issaqueena on Six Mile Creek near Clemson, S. C., erosion along roads was found to be one of the principal sources of reservoir sediment.

Erosion along railroads and power-line rights-of-way is believed to be quantitatively unimportant except in rare instances. What is known of the extent of flood-plain scour suggests that it is not often an important contributor of sediment. Mining and industrial wastes are locally important and are usually readily recognized as sources in a watershed study.

EFFECT OF LAND USE ON EROSION

Acceleration of erosion over geologic norms exists in most sections of the United States and is largely due to man's use and treatment of the land.²³ It follows, therefore, that any program of watershed erosion control must look to means by which the use of the land may be changed or improved in such a manner as to reduce the rate of soil loss and sediment production.

The more important types of land treatment that result in accelerating the rate of erosion are: (1) Burning of vegetal cover (including in addition to intentional burning, accidental burns resulting from man's carelessness, and occasional unavoidable burns resulting from lightning.) (2) Logging and deforestation. (3) Overgrazing. (4) Cultivation. (5) Highway, railroad, and power-line construction. (6) Urban and industrial construction. (7) Mining operations. (8) Smelters.

BURNING

Fire is one of the major causes of destruction of natural vegetal cover. More than 40 million acres of land are burned over annually

²³ Some engineers and geologists have challenged the contention that the sediment load of streams in some sections of the country is any larger now than before occupation of the land by white men. Straub, in discussing an article by the writer (30, p. 312), cited his observations made in 1929-31 in relation to observations made in 1879 by James Seddon on the amount of suspended load transported by the Missouri River past St. Charles, Mo., a point about 30 miles upstream from the river's mouth. Agreement of the two series of investigations was found to be very close, although Seddon's data were compiled at a time when agricultural development in the Missouri Basin was much less than in 1930. Straub concluded from this comparison that although the layer of fertile soil is being severely eroded in many regions of the drainage area, the additional material which is being washed directly into the river in recent years because of agricultural development is not appreciable when compared to the total suspended load of the Missouri. Others, notably Bryan (35) have ascribed accelerated erosion in the arid Southwest primarily to climatic changes during the last century.

in the United States. All fires destroy some of the dead vegetal litter and humic matter of forest and grassland. Many fires are so intense or hot that they destroy not only this ground litter, but completely kill the trees or other vegetation. This destruction of cover leads to acceleration of runoff on slopes bared of their protection, and results in greatly increased soil losses.

Astonishing examples of the effect of burns on the excessively steep, chaparral-covered mountain slopes of southern California have been recorded (fig. 46).

During the 4 days, November 21-24, 1933, a fire swept the mountainous portions of small drainage areas of the San Gabriel Mountains lying northwest of La Cañada Valley, between the San Gabriel and



FIGURE 46.—Severe erosion resulting from burning of chaparral cover on precipitous mountain slopes of the San Gabriel Mountains, Los Angeles County, Calif. (Courtesy U. S. Forest Service.)

Verdugo Mountains in Los Angeles County (121). On December 31, 1933, and January 1, 1934, record precipitation of 10 to about 15 inches fell in the mountain areas. The resulting floods brought erosional debris out of the burned watersheds in amounts ranging from 50,000 to 67,000 cubic yards per square mile. Neighboring watersheds subjected to the same rainfall, but with their chaparral cover intact, yielded almost clear water, which did little damage. In contrast with maximum flood discharges reaching 1,000 second-feet per square mile from the burned areas, the runoff in the unburned San Dimas and Arroyo Seco Canyons a few miles distant was only 50 to 58 second-feet per square mile, and the erosional debris carried out of the San Dimas drainage basin was only 56 cubic yards per square mile (128).

Table 4 (128, p. 38) gives data on measured debris movements from adjacent burned and unburned watersheds of comparable soils and slopes near Los Angeles in the water year 1935-1936.

TABLE 4.—*Measured debris output from burned and unburned watersheds, southern California, in 1935-36*

Watersheds	Area	Total debris output	Rate of debris output per square mile	Watersheds	Area	Total debris output	Rate of debris output per square mile
Burned: ¹	<i>Square miles</i>	<i>Cubic yards</i>	<i>Cubic yards</i>	Unburned: ²	<i>Square miles</i>	<i>Cubic yards</i>	<i>Cubic yards</i>
Fair Oaks.....	0.21	15,715	74,830	Bell No. 1.....	.121	³ 79	652
Fern Canyon.....	.50	15,120	30,240	Bell No. 2.....	.158	10	63
Lincoln.....	.50	7,960	15,920	Bell No. 3.....	.097	⁴ 68	701
Las Flores.....	.32	10,630	33,220	Fern No. 1.....	.055	.3	5.4
West Ravine.....	.25	18,335	73,340	Fern No. 2.....	.063	.1	1.6
				Fern No. 3.....	.084	.1	1.2

¹ The burned watersheds were denuded by fire on Oct. 23, 1935. Records from debris basins, Los Angeles County Flood-Control District.

² The "unburned" areas in Bell Canyon were burned over in 1919, and now are covered with a growth of chamise *Ceanothus* chaparral. The Fern Canyon watersheds have not been burned over in at least 60 years and are now covered with a heavy stand of scrub live oak, big cone spruce, and manzanita-buckthorn chaparral. The Bell and Fern Canyon areas are in the San Dimas Experimental Forest. Records from San Dimas Experimental Forest, U. S. Forest Service.

³ Eroded material came in large part from a road-fill not yet completely stabilized.

⁴ Erosion traced to natural slumps not far above reservoir.

The effect on sedimentation of burns in the drainage area of Gibraltar Reservoir near Santa Barbara, Calif., is clearly shown in table 5. In 1932 and 1933, approximately 80 square miles out of a total drainage area of 216 square miles was burned. During the 2.9-year period between the reservoir surveys in 1931 and 1934, 2,041 acre-feet of sediment accumulate. The average sediment content in inflow to the reservoir during this period was 3.12 percent, or nearly three times as great as during any other period of record. Based on the rate of accumulation for a period of nearly 12 years prior to 1931, it is estimated that approximately 1,600 acre-feet of sediment during the 3 years 1931-34, may be attributed directly to the fire. As the construction of the reservoir cost \$62.00 per acre-foot of storage space, the deposition of sediment attributable to the fire represented a loss to the city of at least \$99,200 or \$1.94 per acre burned. The excessive sediment accumulation during this period led to the construction of the debris dams described on pages 35-36.

In the pine region of the high Sierras of California, a 5-year record (128, p 39) of the runoff and erosion from repeatedly burned and comparable unburned plots shows a yearly runoff from the burned areas

TABLE 5.—*Silting in Gibraltar Reservoir, Santa Barbara, Calif.*

Period	Years	Annual sediment accumulation per acre of drainage area ¹	Average annual inflow	Sediment content of inflow by volume
	<i>Number</i>	<i>Cubic feet</i>	<i>Acre-feet</i>	<i>Percent</i>
1920-31.....	11.8	48	18,458	0.83
1931-34.....	2.9	237	22,586	3.12
1934-36.....	1.55	99	24,839	1.22
1936-38.....	2.55	163	79,765	.50
1938-40.....	1.9	36	11,421	1.15

¹ These figures are based on capacities determined by the Soil Conservation Service from maps of the 1931 and 1934 surveys supplied by the City of Santa Barbara and from the 1936 survey by the Soil Conservation Service. Capacities as of 1920, 1938, and 1940 were determined and reported by the City of Santa Barbara. The data differ slightly from those computed by other agencies from the same maps.

ranging from 31 to 463 times that from the unburned areas, and yearly erosion ranging from 22 to 239 times that from the unburned areas. The runoff from a plot allowed to revegetate after a single burning exceeded the runoff from an unburned check plot by 31 times the first year and 11, 5, 15, and 14 times in the subsequent 4 years.

Table 6, based on records from the soil and water conservation experiment stations of the Soil Conservation Service, shows the effect of burning woodland of the type ordinarily found on farms.

LOGGING AND DEFORESTATION

Most of the commercial logging in the United States has closely approached clear cutting, that is, removal of all trees of sufficient size to contain merchantable timber. Conservative logging, if not preceded or followed by fire, may not destroy much of the undergrowth nor cause severe erosion. Slash left on the ground by logging operations, however, greatly increases the fire hazard, although it is of some benefit

TABLE 6.—*Effect of woodland burning on soil and water losses*¹

Soil and location	Period	Average annual rainfall	Slope	Cover	Ratio of water loss to precipitation	Soil loss per acre
					Percent	Tons
Cecil sandy clay loam, Statesville, N. C.	1932-38	Inches 48.20	Percent 10.0	Virgin woods.....	0.1	0
				Virgin woods, burned annually.....	9.9	2.6
Kirvin fine sandy loam, Tyler, Tex.	1932-40	41	12.5	Virgin woods.....	.3	.05
				Virgin woods, burned annually.....	2.6	.36
Vernon fine sandy loam, Guthrie, Okla.	1932-38	30.63	5.2	Virgin woods.....	.1	.01
				Virgin woods, burned annually.....	4.4	.13

¹ From measurements at soil and water conservation experiment stations of the Soil Conservation Service. All measurements were made on plots 6 by 72.6 feet, or 0.01 acre.

as an erosion-reducing cover if it remains unburned. On the other hand, the high-powered machinery used in large-scale commercial logging operations drags logs over the ground, and tends to destroy much of the lesser vegetation, and to disturb the litter and topsoil, thus leading to serious erosion.

The effect of clear-cutting in a forest and subsequent regeneration by sprouting species has been shown by the results of experiments at Wagon Wheel Gap, Colo. (20). Measurements on two adjacent experimental watersheds of approximately 200 acres each during the period 1910-19 showed that watershed A delivered an average annual sediment load of 691.5 pounds dry weight, and watershed B delivered 568.5 pounds. In 1919 and 1920 all of the timber on watershed B was removed by clear cutting. During the second period of measurement, 1920-26, watershed A delivered an average of 477 pounds and watershed B 3,340.1 pounds of sediment annually. The ratio of B over A, therefore, increased from 0.822 to 7.002, or was about 8½ times as high after cutting—this despite the fact that a dense cover of aspen sprouts took possession of the area the first year after cutting. This increase in sediment load was due in part to the fact that the total yearly runoff in the logged watershed increased after cutting by about 15 percent and the flood crests were advanced in time and their maximum heights increased.

On the Manistee River, Mich., the channel is reported (124, pp. 19-20) to have filled 5 to 8 feet with sediment as a result of logging operations conducted along the river over a period of 30 to 40 years. The practice of skidding logs down the steep sandy river banks, often 50 to 200 feet high, denuded the banks of all vegetation and caused quantities of sand to be pushed and washed into the river. This excessive burden of sand not only clogged the channel but is reported to have caused silting in several downstream reservoirs.

Ritchie (101) recounts an experience in deforestation told by the chief engineer of the Goldfields Water Supply, Western Australia. This agency had experimented on part of the drainage area of Mundaring Reservoir, which supplied all the gold-mining areas and a certain amount of water to the city of Perth. By ringbarking and killing the trees on small areas, the agency had found that more rapid runoff increased the total yield of water, which was ordinarily only 2½ percent of the precipitation and occasionally as low as 2 percent. In an attempt to fill the reservoir in drier years, a large area of the drainage basin was subsequently treated in this manner. As soon as all the timber had been killed, the runoff began to show a most serious increase in dissolved salts, especially sodium and magnesium chlorides. Both of these salts are highly objectionable because of their destructive action on metal pipe lines, and their increase seriously affected use of the water for trade and manufacturing purposes. Finally the water authorities realized the mistake that had been made, and for some years prior to 1923 had been seeking to retrieve the error by pursuing an active policy of reestablishing trees on the ringbarked areas.

A voluminous literature exists on the effects of deforestation in increasing runoff and erosion in many parts of the world, of which typical examples are publications by Glenn (61) on the Southern Appalachian Region and by Wood (138) on southeastern Australia.

OVERGRAZING

Overgrazing, caused by placing too many animal units on an area of land, results in reduction of the density of vegetation through close foraging and overtrampling (fig. 47). On some lands that have steep slopes and highly erodible soils, the running of any animals constitutes overgrazing. On the other hand, virgin range on low slopes may support seasonally as many as 50 or more head of cattle per 100 acres without serious grass depletion. In occasional dry years, of course, the grass cover will be depleted without grazing, and in these years grazing will greatly accelerate the depletion; but recovery will follow in subsequent years of heavy rainfall if the range is given adequate rest.

A study by the Intermountain Forest and Range Experiment Station, U. S. Forest Service, of two watersheds of approximately 10 acres each near the summit of the Wasatch Plateau in central Utah showed that most of the runoff was derived from winter snow, but that by far the greater amount of erosion was caused by summer rains. As a result of grazing restrictions, which allowed the vegetal cover on watershed A to increase from 16 percent in 1920 to 40 percent in 1924, the summer runoff was reduced 64 percent and the amount of sediment lost was reduced 54 percent.

After 1934, watershed B was overgrazed, and by 1936 density of vegetation was reduced approximately from 40 percent to 25 percent. In the latter year, the heaviest summer rainfall, since measurements were started, resulted in record runoff on both areas for a single summer season. The runoff and erosion were found to be greatly increased on watershed B as a result of overgrazing since 1934.

Studies by Craddock and Pearse (40) in the Boise River drainage basin, Idaho, with a portable apparatus for simulating natural rainfall showed that bunchgrass-type range, mainly *Agropyron inerme*, which has the greatest forage value of any local range type if not depleted by overgrazing, yielded an average of only 0.4 percent runoff and 6 pounds of eroded material per acre. The downy chess (*Bromus*



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FIGURE 47.—Contrast of heavily overgrazed slope on left of fence and ungrazed slope on right. On the left of the fence the stage is being set for extensive erosion. Santa Rita Experimental Range, 8 miles east of Sonoita, Ariz. (Courtesy U. S. Forest Service.)

tectorum L., needlegrass (*Stipa lettermani*), and lupines (*Lupinus* sp.) which have succeeded the bunchgrass on overgrazed ranges at lower and higher elevations, respectively, were found to be distinctly less effective covers. Runoff, ranging from 60 to 100 times as much, carried off an average of 2,017 and 4,785 pounds of soil per acre from these types. Areas covered by an annual weed type of vegetation yield 150 times as much runoff as those growing bunchgrass, and approximately 15,280 pounds of soil per acre.

In a study of the relation of sedimentation in Morena Reservoir, San Diego County, Calif., to watershed characteristics, Barnes, Kraebel, and LaMotte (18) concluded that most of the sediment had come from deep trenching of alluviated valleys and from mountain slopes denuded of their protective cover by fire. They found that overgrazing and repeated burning have been the chief causes of accelerated erosion, which is still active, and of annual sediment accumulation in the reservoir of 174 cubic feet per acre of drainage area.

A number of studies (128, pp. 47-48) have shown that grazing of farm woodlots results in significant increases in runoff and soil loss. Other studies have shown that the nutrition obtained from woodland grasses is definitely inferior to that obtained from grasses of open pastures. At the soil and water conservation experiment station, Soil Conservation Service, at La Crosse, Wis., measurements were made on three small watersheds: (1) A pasture recently cleared of timber, (2) a watershed covered with typical hardwood forest that is being pastured, and (3) a typical wood lot upon which no grazing of any kind is permitted. From May to November 1935, in which period there were 8 rather intense storms, but little more than normal average precipitation, the grazed wood lot yielded about 9 percent runoff and 1,600 pounds of soil per acre, the cleared pasture 3 percent runoff and 600 pounds of soil per acre, and the ungrazed wooded watershed only 0.15 percent runoff and 17 pounds of soil per acre.

CULTIVATION

Of all the forms of land use, cultivation has undoubtedly resulted in the greatest destruction of soil and the greatest increases in the sediment burden of streams. Of the total of 1,903 million acres of land in the United States, about 413 million are tilled or tillable cropland; approximately 615 million acres are classed as commercial forest land; pasture and range, exclusive of grazed forest and woodland areas, total about 696 million acres; and farmsteads, roads, urban developments, waste, and similar areas account for the remaining 179 million acres.

Bennett (22) has discussed comprehensively the effects of clearing and cultivation of the land on the acceleration of erosion. These effects are now so widely recognized and understood in the United States that it is repetitious to discuss them in any detail here (fig. 48).



7-104

FIGURE 48.—Contrast of erosion in cultivated apricot orchard and pasture on land sloping up to 55 percent. Ventura County, Calif., February 1934.

TABLE 7.—*Soil and water losses under clean-tilled crops and dense cover*¹

Soil and location	Period of measurement	Annual rainfall for the period	Slope	Clean-tilled			Dense cover		
				Crop	Annual soil loss per acre	Ratio of water loss to precipitation	Cover	Annual soil loss per acre	Ratio of water loss to precipitation
		Inches	Percent		Tons	Percent		Ton	Percent
Clinton silt loam, La Crosse, Wis.	1933-38	33.70	16	Corn....	111.8	28.7	Bluegrass.....	0.10	5.1
Muskingum silt loam, Zanesville, Ohio.	1934-40	39.76	12	do.....	94.6	42.4	Native grass.....	.03	6.4
Cecil sandy clay loam, Statesville, N. C.	1932-38	48.20	10	Cotton..	33.9	12.1	Mixed grasses....	.01	.2
Marshall silt loam, Clarinda, Iowa.	1933-40	26.70	9	Corn....	32.0	15.3	Bluegrass.....	.02	2.0
Shelby silt loam, Bethany, Mo.	1931-40	30.26	8	do.....	50.9	27.1	Timothy-bluegrass	.16	8.1
Stephenville fine sandy loam, Guthrie, Okla.	1930-38	30.63	7.7	Cotton..	18.9	12.5	Bermuda grass....	.02	1.0
Austin clay, Temple, Tex.	1931-40	31.64	4	Corn....	18.8	12.9	do.....	.02	.03

¹ From measurements at soil and water conservation experiment stations of the Soil Conservation Service. All measurements were made on plots 6 by 72.6 feet, or 0.01 acre.

Table 7 gives a comparison of soil losses on plots of clean-tilled crops and dense cover at the soil and water conservation experiment stations of the Soil Conservation Service.

Bennett (22, pp. 149-168) has also given detailed comparisons of soil losses with different degrees and lengths of slope, with rainfall intensity, season, crop rotation, cropping practices, direction of cultivation, organic matter, grass and forest, past degree of erosion, and biological aspects of the soil.

HIGHWAYS, RAILROADS, AND POWER LINES

One of the important sources of erosional debris throughout most of the United States is the widespread network of highways and county roads. Much attention has been given in recent years to the vegetative stabilization of highway cuts and fills, but few data are available on relative contribution of sediment from these sources. Data previously cited (p. 115) show that in the Lexington Reservoir drainage area, N. C., roads have contributed a total of 2 percent of the past sediment output; and in the Tallahatchie drainage area, northern Mississippi, 2 to 11 percent. Johnson and Brown (75) found that roads were a major source of sediment in the drainage area of Lake Issaqueena near Clemson, S. C., but no data on the quantities of sediment from this source were obtained. It was estimated in their survey, however, that 33.3 miles of road in this area of 14 square miles were contributing considerable amounts of sediment and, hence, were in need of erosion control.

The percentage of the total sediment output contributed by roads may vary from almost 100 percent in some watersheds to a negligible amount in others. Modern scenic highway construction across well-forested mountains in both the Appalachians and the Rocky Mountains has caused soil disturbance of serious proportions for the first time

since settlement of this country. In such mountain watersheds, streams that once issued almost crystal clear are now muddy with sediment derived from highway cuts and fills. From the meager available data it appears that in most agricultural drainage areas the contribution of roads ranges from about 2 percent to as much as 15 percent or more.

A serious erosion problem in many parts of the country stems from road and highway drainage. In the southern Piedmont, for example, large areas of gullying in fields may be traced directly to improper diversion of road water. Federal and State highways, because of their greater cost and value, are better protected against slope and fill erosion and are more properly drained. Throughout most of the country, county highways and secondary roads are causing more serious erosion than the main roads.

In most of the country, railroad fills and cuts have been in place for so many years that they are now more or less completely stabilized by vegetation. It has been generally observed, however, that while railroads have taken active measures to keep the fills well vegetated as a means of reducing maintenance, they have generally neglected the cuts, which are protected only where they have become covered by vegetation through natural seeding, over a period of many years, and not until they have washed down to relatively stable slopes.

In some sections a minor problem has been caused by clearing of lanes for cross-country power transmission and pipe lines. These lanes are similar to fire breaks cut out in brushy areas in some sections of the country, notably in southern California. Much controversy has arisen as to the ultimate value of these fire breaks, as it appears that in some places they have resulted in a great deal of erosion, which some infer has more than offset their value in fire protection.

URBAN AND INDUSTRIAL CONSTRUCTION

The disturbance of soil by urban and industrial construction may result temporarily in a large increase in the sediment load of streams. The environs of such projects, however, are usually sodded or otherwise protected from erosion soon after the construction work is finished.

An example of the effect of construction activities is shown by the survey of Greenbelt Lake (17), a recreational development, at the Greenbelt, Md., suburban housing project of the Federal Public Housing Authority. This reservoir, constructed in July 1936 with an original capacity of 196 acre-feet, was found to have accumulated 10-acre-feet of sediment in 1.6 years from a drainage area of only 530 acres. This rate of sedimentation is equivalent to more than 500 cubic feet of sediment annually per acre of drainage area; but as three-fourths of the drainage area was covered by second-growth woodland and vegetated idle land, which showed no indications of erosion, it is evident that nearly all this material came from the one-fourth of the area in which the Greenbelt housing project was under development. If so, the actual contribution from the construction area was approximately 2,000 cubic feet per acre per year. By the end of 1938, however, all of the ground of this project was sodded, drainageways were protected by either rock-lined channels or by grass, and it is to be expected that further silting in the lake will be negligible.

The annual sediment accumulation per acre of drainage area in Greenbelt Lake was approximately 10 times as great as the average output of agricultural watersheds in the southern Piedmont. The output of erosional debris from the construction area was probably 40 times as great during the short period of activity. One additional factor contributing to this high rate, however, is the fact that the watershed is very small, and no places for deposition above the reservoir exist.

Another example of the effect of urban development is Lake Concord, near Concord, N. C., which had an annual sediment accumulation of 117 cubic feet per acre of drainage area during the 10 years 1925-35 (45, pp. 49-52). This rate of accumulation, which is about three times the average of reservoirs, and higher than any other single reservoir in the southern Piedmont, is attributed to the expansion of the mill town of Kannapolis into the drainage area after the lake was built. Large numbers of low-cost houses were built in the decade, grounds were poorly protected, and miles of unpaved streets and new roads were cut through the area.

MINING AND QUARRYING

In some areas mining wastes constitute a significant, if not major, part of the sediment load of streams. This is particularly true in the areas of gold placer and hydraulic mining in the Western States, notably California, and in the coal-mining regions of the Appalachian Mountains, especially Pennsylvania.

Gilbert (60), in his classic study of hydraulic mining debris in the Sierra Nevada drainage basins in California, estimated that between 1849 and 1914 approximately 1,665 million cubic yards of debris was produced by hydraulic mining operations in the watersheds of the Sacramento River and other streams entering Suisun Bay. He estimated that during the same period the production of nonmining debris resulting from soil erosion, erosion on trails, and natural erosion produced approximately 700 million cubic yards.

At the Holtwood Reservoir of the Pennsylvania Water & Power Co. on the Susquehanna River, Pa., a subsidiary steam generating plant, which has been in operation for a number of years, obtains a supply of fuel from dredging of deposits from the reservoir and separation of the culm or fine coal from the sand and silt. It has been estimated that 10 million tons of coal were recovered from Pennsylvania streams prior to 1925, and that streams in and draining from the anthracite region contain at least 900 million tons of material carrying enough coal for profitable recovery (112). The annual production of stream-borne silt from anthracite mining operations in Pennsylvania was estimated to be 8,900,000 tons in 1925; and of fine coal, 1,150,000 tons.

In order to maintain a 30-foot channel in the lower Schuylkill River below the Fairmount Dam, it is necessary to excavate about 1 million cubic yards annually. The material excavated has been found to be a mixture consisting of about half culm and half mud (97).

SMELTERS

Complete destruction of natural vegetation by the sulfurous fumes from smelters, and occasionally fumes from other industrial plants, has resulted in some of the most spectacular erosion to be found any-

where in America. At Ducktown, Tenn., fumes from a copper smelter killed all natural vegetation in an area of 10 to 12 square miles, except for occasional clumps of sage grass and wild smilax. Over a much larger surrounding area, vegetation is sparse or stunted. For a number of years now, the sulfurous fumes have been used to manufacture sulfuric acid, instead of being released into the air, and the vegetation is gradually coming back. Both runoff and erosion from this area have been at a rate many times greater than in other parts of the Appalachian Mountains (61).

A similar situation prevails near Kennett, Calif., where all vegetation has been destroyed by smelter fumes on an area of 67,000 acres, and partially destroyed on 86,000 acres. Soil washing and gullyng has been rapid. It has been estimated (126, p. 326) that a total of more than 35 million cubic yards of soil was removed from the Kennett area in 10 to 15 years. Comparable conditions also prevail near Anaconda and Butte, Mont., and in other areas of the country where smelters have operated.

METHODS OF EROSION CONTROL

All of those works of man and nature that tend to counter and reduce the effects of land use in accelerating erosion should be considered as methods of erosion control. In some drainage areas, even large ones, the value of reservoirs and other engineering developments that are subject to rapid damage by sedimentation may dictate a removal of all land in the drainage area from immediately productive use, and the dedication of this land solely to watershed protection. This type of erosion control is only a form of insurance—the payment of a lump-sum premium for loss of future returns from the land, in order to assure prolonged service value of the reservoir. In other areas high land values or sound public policy may require the land to be kept in use for agriculture or other purposes, but a variety of control methods can be used to keep sediment production to a minimum. The methods that contribute to erosion control are many and varied and can be outlined here in only a very summary manner.

AFFORESTATION AND FOREST MANAGEMENT

In those sections of the United States that were originally clothed with forest, the reestablishment of forests and proper forest management, including fire control and exclusion of grazing, offers generally the surest means of protecting the drainage areas of reservoirs. Not only do forests when well-established and maintained show rates of erosion generally lower than those from any other type of land use, but they tend also to conserve precipitation and to equalize runoff. With well-forested drainage areas, no other means of sedimentation control are usually necessary.

Afforestation for reservoir protection should be carried out in a scientific manner; and to aid in accomplishing this, the services of State forestry agencies and the United States Forest Service are available in all sections of the country to advise and assist reservoir owners. Proper afforestation and forest management will not only provide the desirable qualities of watershed protection, but scientific timber cutting with due safeguards against erosion will provide a valuable source of income over a long-term period (fig. 49).



LA-10228-A; LA-10228-B

FIGURE 49.—A, Badly eroded cottonfield on 18-percent slope planted in young pine seedlings by CCC enrollees, near Homer, La. B, Same field 2 years later. Survival of short-leaf pines planted 1,650 to the acre was 95.4 percent. The ground already well protected by litter.

Lathrop (81) has listed seven reasons for advocating the planting of forest trees on reservoir watersheds:

1. A growing crop improves the property.
2. Pine and spruce trees planted near the edge of reservoirs prevent leaves of deciduous trees from blowing into the water where they cause color and promote taste and odor problems.
3. Trees prevent soil erosion on the area planted and so reduce turbidity.
4. A forest provides attractive recreational areas.
5. In time, a forest may provide a profitable timber-crop.
6. Owners of waste or unproductive land are thereby stimulated to plant such land to forest trees.
7. Such reforestation can change desolate areas into beautiful ones. A reservoir surrounded by pine forests may compare favorably with a well-landscaped estate.

Rodwell (103) has compared the turbidity of water flowing from contiguous areas in England, similar in character and elevation but separately drained, one of which has been afforested, another partly forested, and a third left bare. These results are shown in figure 50. Although records of the rate of runoff and the amount of heavy debris carried were not available to Rodwell, he considers the comparative turbidities suggestive of the beneficial effect of afforestation.

Ashe (16) has pointed out that brush may give as much protective efficiency as forests, but brush provides no merchantable products and is therefore not so economical in the long run. He maintains that grass would not have so much protective efficiency as forests in the Rocky Mountains south of Idaho and in the southern Appalachian or Piedmont regions where protection is urgently needed. In these regions, he asserts, there are many types of soil and many sites, such as warm and dry southern slopes, on which a permanent sod cannot be maintained. Furthermore, the forest produces a more permeable soil than grass, because the root zone, 3 to 4 feet deep, which is penetrated by many channels resulting from the decay of roots and rootlets, allows greater percolation.

The two great enemies of watershed protection by forests are fire and grazing. The effect of both has already been pointed out. A very necessary adjunct to afforestation by reservoir owners is provision for adequate fire protection, and planning for emergency revegetation of areas that may be burned in occasional unavoidable fires.

Grazing should be prevented or greatly restricted in forested areas devoted to watershed protection, for it reduces the efficiency of these areas in controlling sediment production and creates a greater hazard of stream pollution. Grazing in woodland results in the destruction of sprouts of new trees, disturbs the litter, compacts the soil, and causes more rapid runoff, and consequently greater sediment production.

Of nearly 2 million acres of land reforested by the United States Forest Service to 1933, the total cost, including all items from seed collection through field planting, ranged from \$3 per acre for the easily planted sites in the Lake States, where seedling stock is used and the soil is free from rock and easily worked, to as much as \$14 to \$25 per acre on the more difficult sites in other regions. Plantings in the South that cost \$5 to \$8 per acre in the 1920's could be established for as little as \$3 per acre by 1933 (126, p. 1497). The cost of Soil Conservation Service farm woodland planting on bare areas has ranged from \$4 to \$30 per acre, averaging \$14.28 for 60,318 acres.

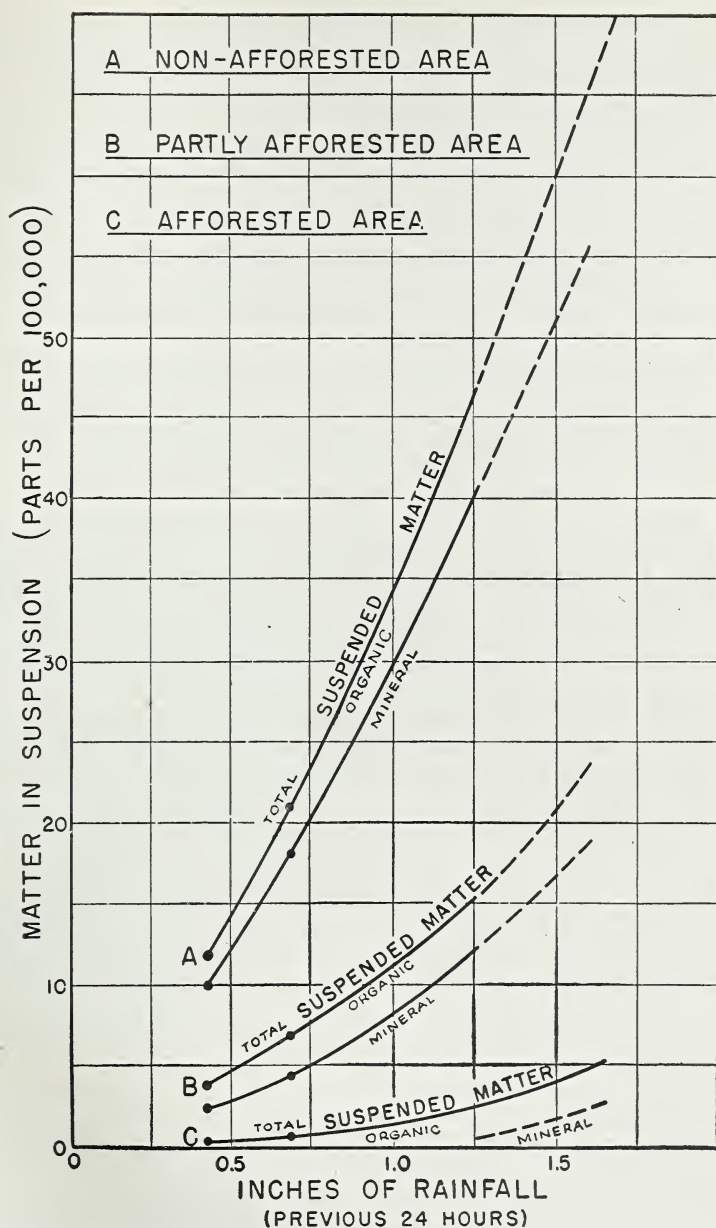


FIGURE 50.—Concentration of suspended matter in runoff from nonforested, partly forested, and forested watersheds in England. (After Rodwell.)

Lathrop gives the minimum cost of forest planting in Ohio as \$6 per thousand trees, of which \$3 is the price of trees at the State forest nursery and the remainder is the cost of planting. He notes that a 90 percent survival is excellent, even under good weather conditions, and that 60 percent survival was the average over 10 years in the

Mahoning Valley Sanitary District plantings. Other causes of loss are fire, damage by disease and insects, crowding out and death from shading by unequal growth of the stand, and theft of evergreens for Christmas trees. About one-fifth of the trees planted may be expected to reach the marketable timber stage.

Maintenance costs required for adequate fire protection in State, private, and other forests have been estimated to range from \$0.0139 to \$0.0839 per acre (*126, p. 1411*).

Kotok and Kraebel, discussing a paper by Eaton (*46*), describe the practice of reseeding burned watersheds in southern California with mustard as an emergency measure of erosion control. They state that the cost is \$1.25 per acre when the seed is sown by hand, and \$0.90 per acre when sown from an airplane.

A comprehensive discussion of the whole problem of afforestation and forest management will be found in a congressional report (*126*), and Bennett (*22, pp. 421-433*) has summarized forestry and woodland management in their relation to soil and water conservation.

REGRASSING AND GRASSLAND MANAGEMENT

Revegetation of an area with grasses or perennial shrubs, vines, and succulents is an alternative to afforestation in climatic forest zones, and a primary method in climatic grassland zones. In the prairies and plains of central United States, which were not forested in their primeval condition and in which precipitation is too scant to produce timber trees, the use of grasses and low-growing vegetation is the most logical method of permanent watershed protection.

Table 7 shows the great contrast in the sediment-producing characteristics of land in permanent sod and land in cultivation. Measurements on plots on similar slopes and soils at the soil and water conservation experiment stations of the Soil Conservation Service have shown that soil losses are negligible from either virgin woodland or permanent sod.

Where either grass or woodland may be used, grass has the advantage of generally affording quicker protection, often reducing erosion from high to negligible rates in one season, and it is less subject to fire hazard than woods. Woodland, on the other hand, is usually considered to be of more permanent value, yielding generally greater returns over a long period for a lower cost of upkeep. Woodland may have a greater effect in stabilizing stream flow and offers other esthetic values not afforded by grass.

A grass sod may be developed on most lands, by seeding, if adequate attention is given to fertilization. In some very actively eroding areas, as gullies and waterways, however, it may be desirable to establish a cover rapidly by sodding. Plants other than grasses can be established more rapidly and cheaply in some sections. Such a plant as kudzu has been found particularly valuable in the Southeastern States on most types of soil.

Bennett (*22, pp. 378-418*) has described the native and imported plants useful in establishing a dense vegetal cover. He has advocated strongly the maintenance of a ground cover for erosion control, even of weeds, if necessary, until they can be replaced by more desirable plants.

The effect of vegetation and grazing control is comprehensively discussed in *The Western Range* (127).

Bryan, in discussing a paper by Taylor (116, p. 1707), points out that vegetation is most effective in decreasing erosion on hill slopes, on alluvial fans, and at the heads of gullies, and that after the water is concentrated in the valley floor, a good growth of grass tends to spread the water and cause deposition of the sediment. A decrease in vegetation, particularly grass, whether brought about by overgrazing or change in climate to greater aridity, causes the formation of a channel. Thus, even though general erosion may decrease with a smaller amount of runoff, a special and concentrated stream erosion may ensue and the production of sediment may be greater. Successful erosion control in the arid Southwest, Bryan says, depends upon (1) reasonable restriction of grazing; (2) introduction of drought-resistant plants that are not palatable to stock, such as salt cedar; and (3) construction of retarding and retaining works.

Proper maintenance of grassland may require occasional reseedling, fertilizing, especially liming, and rigid grazing control. Contour furrowing on pasture and range land has also been found beneficial in conserving moisture and increasing the stand of grass. Based on experience of the Soil Conservation Service, contour furrows 3 inches deep, 12 inches wide, and 84 inches apart, made with a single row lister pulled by four horses, have cost an average of \$0.27 per acre. Ridges made with a turning plow, spaced 40 to 50 feet apart, have cost an average of \$0.10 per acre.

It has been found that the cost of establishing a fine Kentucky bluegrass or Bermuda grass sod on steep eroded areas in the Ohio Valley Region is \$10 or more per acre, including seed, lime, and fertilizer. Under suitable treatment these areas become sufficiently productive within a few years to carry one head of livestock on 3 or 4 acres without damage by erosion.

Costs for artificial reseedling of ranges have been estimated by the Forest Service as follows (127, p. 506):

Assuming that an ample seed source will be developed as needed, and that a market price of around 15¢ per pound may be expected, the cost, using a grain drill and 4 to 5 pounds of seed per acre and figuring on failure half the time, should not exceed \$2.50 to \$3.00 per acre. With hand seeding and trampling in by livestock the cost for two seedings should not exceed \$1.50 to \$2.50 per acre.

Soil Conservation Service costs for range reseedling have ranged from \$1.70 to \$4.43 per acre, averaging \$2.15.

CULTIVATION PRACTICES

In many sections of the United States, especially in most parts of the great farming region of the Middle West, it is impossible to select a reservoir drainage area that does not contain a high percentage of fertile land, which from the standpoint of national economy as well as cost, could not be feasibly withdrawn entirely from cultivation. When reservoirs are located in such areas, it is especially important that all available measures of conservation be adopted to reduce sediment production to a minimum without sacrificing the relatively high level of crop production.

Following is a brief description of the nature and effects of the more important soil-conserving practices advocated for cultivated

land by the Soil Conservation Service. All of these practices have been described fully by Bennett (22) and in various publications of the Department of Agriculture (125). Reservoir owners should encourage their adoption in the fullest measure on lands that must be cultivated in the reservoir drainage areas.

Crop Rotation.—Crop rotation is a practice of planting a recurrent succession of different crops on a single piece of land. Commonly, a cultivated crop, a small grain, and a grass, legume, or legume-grass mixture are planted in successive seasons or years, although one or more of the crops may be planted for more than 1 year in succession. As only the cultivated crop allows the maximum erosion, the net effect of the rotation is almost invariably a reduction in the soil and water losses. A good rotation, by maintaining the fertility of the land, nearly always yields a greater net return over a long-term period.

TABLE 8.—*Soil and water losses under single crop cultivation and under rotation*¹

Soil and location	Period inclusive	Annual rainfall	Slope	Crop	Annual ratio of water loss to precipitation	Annual soil loss per acre
		<i>Inches</i>	<i>Percent</i>		<i>Percent</i>	<i>Tons</i>
Clinton silt loam, La Crosse, Wis.	1933-38	33.70	16.0	{3-year rotation average ² . {Corn continuously.....	16.9 28.7	28.0 111.8
Muskingum silt loam, Zanesville, Ohio.	1934-40	39.76	12.0	{4-year rotation average ³ . {Corn continuously.....	21.2 42.4	13.3 94.6
Cecil sandy clay loam, Statesville, N. C.	1932-38	48.20	10.0	{4-year rotation average ⁴ . {Cotton continuously.....	9.4 12.1	15.1 33.9
Kirvin fine sandy loam, Tyler, Tex.	1931-40	40.66	8.8	{3-year rotation average ⁵ . {Cotton continuously.....	17.3 25.5	17.2 58.6
Shelby silt loam, Bethany, Mo.	1931-40	30.26	8.0	{3-year rotation average ⁶ . {Corn continuously.....	16.2 27.1	9.1 50.9
Vernon fine sandy loam, Guthrie, Okla.	1930-38	30.63	7.7	{3-year rotation average ² . {Cotton continuously.....	10.2 12.5	4.2 18.9

¹ From measurements at soil and water conservation experiment stations of the Soil Conservation Service. All measurements were made on plots 6 by 72.6 feet, or 0.01 acre

² Rotation of barley, clover-timothy, and corn.

³ Rotation of wheat, corn, and meadow for 2 years.

⁴ Rotation of wheat-lespedeza, lespedeza, cotton, and corn.

⁵ Rotation with cover crop (oats) of cotton, corn, and lespedeza (1931-35), and cotton, sorghum, and cowpeas (1936-40).

⁶ Rotation of corn, wheat, and clover-timothy.

Rotations are already widely used in many sections of the United States and abroad. Table 8 gives data from plot measurements showing the effects of rotations.

Increasing Organic Matter.—It has been found by experiment and observation that the addition of vegetal or organic matter to the soil is generally highly effective in reducing runoff and soil losses. For example, at the soil and water conservation experiment station at Clarinda, Iowa, application of 16 tons of manure per acre to Marshall silt loam cultivated to corn on a 9-percent slope resulted in only one-fifth as much soil loss as occurred on an unmanured plot under the same conditions. The practice of plowing under a cover crop, such as clover, vetch, lespedeza, peas, crotalaria, or alfalfa, in order to increase the organic matter in the soil achieves similar effects.

Mulching.—Mulching is the practice of spreading a layer of organic material over the surface of the soil to reduce the concentration and rate of runoff, and hence the soil loss. At the soil and water conservation experiment station, Statesville, N. C., measurements from 1934 through 1936 showed that bare Cecil sandy clay loam on a

10-percent slope lost only 0.19 tons of soil per acre annually when covered by a 2-inch layer of undecomposed pine needles, and 0.15 tons under a 2-inch layer of undecomposed hardwoods forest litter. A comparable plot cultivated continuously to cotton lost 32.26 tons of soil per acre annually.

The use of crop residues for mulching is one of the cheapest and most effective means of erosion control. Grain straw, corn stalks, cotton stalks, tobacco stalks, small grain stubble, and the refuse from potato plants, if scattered over the bare land during periods when the soil is not under cultivation, will have a decided effect in reducing the rate of erosion. It is particularly important that this should be done in preference to burning these residues, a practice common in many sections of the country.

Very recently a new practice known as stubble mulching has been developed that shows promise of answering a long-felt need for a method of cultivation that would not expose bare soil to erosion. In this method a new type of plow is used that cultivates without turning under the stubble of the preceding crop but leaves it rightside up until the next planting season (23).

Seasonal Cover Crops.—Seasonal cover crops are planted to protect the land against erosion, and usually also for some economic return in periods between use of the land for major cash or feed crops, such as corn, cotton, or grain. Such crops may or may not be turned under for green manure. The erosion-resisting effect of seasonal cover crops is only slightly less, while they are on the ground, than the effect of a dense sod, as shown in table 7. Cover crops frequently used in the more humid sections of the United States for winter cover protection are the vetches, field peas, clovers, and certain ryes. Cover crops commonly used for summer planting are lespedeza, the crotalarias, and cowpeas.

Contour Cultivation.—One of the cardinal principles of soil conservation is the cultivation of all intertilled or row crops on the contour instead of up and down the slopes (fig. 51). Contour cultivation has been found in numerous experiments to be highly effective in reducing the rate of runoff and soil losses. Some of the results of these observations are shown in table 9. Furthermore, on most topography, contour cultivation saves power and time and, therefore, reduces costs of cultivation. Contouring is a necessary adjunct to contour strip

TABLE 9.—*Soil and water losses under straight-row cultivation and contour cultivation*¹

Soil and location	Period of measurement	Annual rainfall for period	Size of area	Slope	Straight rows		Contour cultivation	
					Ratio of water loss to precipitation	Soil loss per acre	Ratio of water loss to precipitation	Soil loss per acre
		<i>Inches</i>	<i>Acres</i>	<i>Percent</i>	<i>Percent</i>	<i>Tons</i>	<i>Percent</i>	<i>Tons</i>
Shelby silt loam, Bethany, Mo.	1935-41	33.05	24.49	6.7	16	163.67		
Houston black clay, Temple, Tex.	1932-41	32.99	7.51	6.5			14	21.31
Houston black clay, Temple, Tex.	1932-41	33.70	.0309	3.5	13.6	15.72		
			.0847	3.5			4.65	5.89
	1931-41	32.74	.01	4	7.65	10.16		
			.01	4			4.7	3.93

¹ From measurements at soil and water conservation experiment stations of the Soil Conservation Service.

² 4.85 acres prior to May 1934.



LA.—10291

FIGURE 51.—Contour plowing and terrace, Claiborne County, La.

cropping and should be used in connection with terracing. On gentle slopes contouring alone is often a sufficiently effective measure of erosion control. In dry-land areas the practice of damming or forming basins in the rows with a basin lister is often used in contour cultivation to conserve water on the field.

Strip Cropping.—Strip cropping is a system under which ordinary farm crops are planted in relatively narrow strips, so arranged that strips of erosion-resistant crops are separated by strips of close-growing erosion-resistant crops (fig. 52). There are three main types of strip cropping: (1) Contour strip cropping, in which the strips are planted on the contour; (2) field strip cropping in which the strips are laid out parallel, generally with field boundaries, and not necessarily on the contour; (3) wind strip cropping in which farm crops are planted in straight parallel strips at right angles to the direction of prevailing winds. Contour strip cropping is by far the most important in controlling water erosion. The effects of strip cropping in reducing soil losses are shown in table 10. Contour strip cropping of

TABLE 10.—Soil and water losses with and without strip cropping¹

Soil and location	Period of measurement	Annual rainfall for period	Size of area	Slope	Without strip crops		With strip crops	
					Ratio of water loss to precipitation	Soil loss per acre	Ratio of water loss to precipitation	Soil loss per acre
Shelby silt loam, Bethany, Mo.	1938-41	Inches 26.88	Acres 0.279	Percent 6.6	Percent 7.7	Tons 1.91	Percent 7.6	Tons 0.85
Bowie fine sandy loam, Tyler, Tex.	1935-38	38.40	.666	5.5	11.5	17.56	11.8	5.89
Kirvin fine sandy loam, Tyler, Tex.	1933-41	42.23	{ 6.05	7.5	20.1	48.01	19.8	10.93
			{ 2.64	5.5				

¹ From measurements at soil and water conservation experiment stations of the Soil Conservation Service.

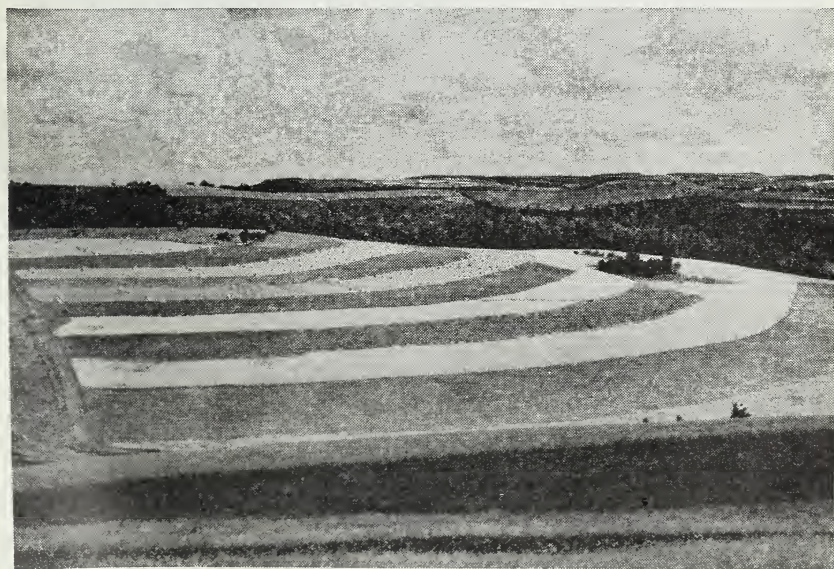
necessity includes contour cultivation and often, if the land is especially erodible, terraces are combined with strip cropping.

The cost of installing strip cropping has been found by the Soil Conservation Service to range from only a few cents per acre to \$10 or more per acre. The average cost on 149,329 acres was \$2.60.

Terracing.—Terraces are channels or benches constructed on the contour or on a low grade on sloping lands as a means of disposing of runoff slowly and gradually. Field terraces and hillside ditches are one of the oldest methods of erosion control. In ancient lands remnants of bench terraces can be traced to the pre-Christian era, this type of terrace having been highly developed in China, Japan, Peru, and parts of the Near East. Terracing of various types has been used in America, especially in the South, since colonial times.

Basically, there are three types of terraces: (1) The bench terrace consists of a series of steplike benches that are nearly flat on their surface and are separated by steep, heavily vegetated, or walled risers. These terraces are designed to reduce the slope of cultivated areas and to make exceptionally steep land available for cultivation. (2) The graded-channel terrace, designed to intercept and divert runoff in channels having grades that will prevent erosive velocities of flow. The cultivated land between terraces remains on its original slope (fig. 51). (3) The level terrace, designed to impound runoff primarily for the conservation of precipitation. This terrace is used largely in the drier, flatter sections of the United States.

The modern practice in the humid sections is to construct broad-based terraces of the graded-channel type, and to support these adequately by cropping and tillage practices. In many soils such terraces provide one of the most effective erosion-control measures applicable



N. Y.—374

FIGURE 52.—Strip-cropped field in 4-year rotation, 2½ miles west of Wallace, Steuben County, N. Y.

to cultivated land. If improperly constructed or not adjusted with proper land use practices, however, terraces may be overtopped by runoff and may accelerate rather than retard soil losses.

Few quantitative data have been obtained on the effects of terracing versus lack of terracing, with other erosion factors being equal. The best available data are from the soil and water conservation experiment station of the Soil Conservation Service at Bethany, Mo. Here two small cultivated watersheds in Shelby silt loam, one terraced and one unterraced, were compared during a 7-year period, 1935-41. The unterraced watershed of 4.49 acres with an average slope of 6.7 percent received an average annual rainfall of 28.34 inches and had an average annual runoff of 15.9 percent and a soil loss of 23.38 tons per acre. The terraced watershed of 8.03 acres with an average slope of 7.0 percent and the same rainfall had an average annual runoff of 11.6 percent and a soil loss of only 0.54 ton per acre.

With favorable soil conditions and slopes, and efficient machinery, the costs of terracing may run no higher than for plowing the same field. With heavy soil, rocks, stumps, gullies or irregular topography, the cost may run as high as \$30 per acre, including installation of proper water-disposal works. On projects of the Soil Conservation Service the average cost of terracing on 178,222 acres in all sections of the country was \$8.93 per acre. The cost per mile of terrace for surveying and construction averaged about \$52.

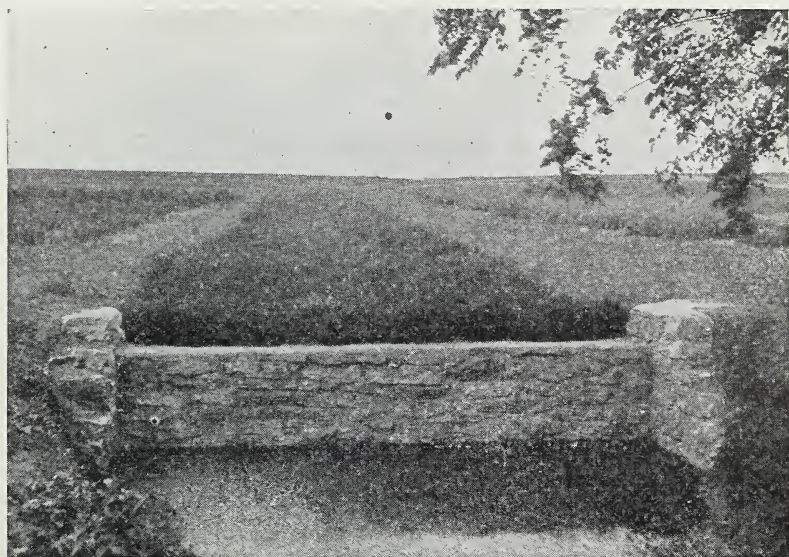
PROTECTED CHANNELWAYS

The areas of greatest erosion hazard on most land are the drainageways leading from perennial streams in an intricate pattern to all parts of the land surface. These drainageways are the natural channels for collection and conveyance of runoff to the main streams, and any disturbance of the protective cover on them may allow concentrated flow to scour out great quantities of soil. Originally, because of the greater moisture, vegetation was especially dense in these drainageways, and they were naturally protected against erosion. One of the principal problems today in erosion control is to restore and protect these drainageways by all possible methods, so that they may again convey the runoff without soil loss (fig. 53). The establishment of practical runoff-disposal systems in connection with other conservation practices, such as terracing and strip cropping, is one of the important aspects of soil conservation planning.

GULLY CONTROL

The term "gully," as used in this publication, refers to a water channel developed or greatly enlarged as a result of accelerated soil erosion within historic time. Surveys of the Soil Conservation Service have shown that more than 200 million gullies have developed in this country since white men first began to occupy the land. New gullies by the thousands are being developed every year. The principal causes of gullying are (1) removal of protective vegetation, often followed by methods of cultivation that tend to concentrate runoff in certain parts of the field, (2) construction of faulty water channels, such as ditches, terraces, and diversions, (3) improper diversion of drainage from roadways, (4) livestock trails and overgrazing, (5) mining operations, and (6) destruction of vegetation by smelter fumes.

Prevention of the formation of gullies is much simpler than restoration of the land after it has been subject to such channeling. Proper methods of cultivation, forestry, grazing control, and other conservation practices are effective in preventing the formation of gullies. Incipient gullies may often be checked by redirecting the drainage from roadways, filling in ruts and trails with straw, relocating fences to shift stock trails, and similar practices. After gullying has a head start in a field, the cost of its control is often greater than the value of the field's production for many years. Therefore, the justification for gully control must often rest with the benefit to reservoirs and other developments downstream that are being affected by the sediment output. It has been pointed out under Sources of Sediment,



ILL.—674

FIGURE 53.—Sodded field drainage way protected by masonry dam. Terrace drainage is diverted into this waterway. Total drainage area above the dam is about 30 acres.

p. 115, that gullying in many areas is one of the most important causes of excessive sediment production, and certainly gully control should be one of the first aspects to be examined in planning a control program for reservoir protection.

Gully control may be classified under three headings: (1) Diversion of runoff away from the gully, including retention of rainfall on the watershed to prevent runoff, (2) vegetative control, including sloping of the gully sides if necessary, and (3) check dams to stabilize the bed and prevent further cutting. A practical solution of control of many gullies will require a combination of these methods.

Methods that aid in preventing runoff from reaching gullies or areas of potential gullying include subsoiling, contour furrowing and listing, absorptive-type terraces, and earth fills to create small ponds above gullied areas. Diversion of runoff through terraces or ditches from the head of the gully to other waterways which are sodded with grass or lined with nonrodible material in advance of diversion is

an effective means of preventing further cutting in the gully. If it is not possible to keep water out of gullies, control of erosion within the gully may be obtained if vegetation can be established in the bottom or if mechanical structures built at critical points will prevent down cutting and allow vegetation a chance to gain control.

Bank sloping by hand or machine may be necessary in large, caving-head gullies in order to establish a slope on which vegetation can take hold. In many areas gullies will be covered with vegetation naturally if the banks are properly prepared, and if livestock, fire, and other causes of disturbance are kept out of the gullied area. For more rapid control, however, planting or seeding with trees, shrubs, vines, or grasses is necessary (fig. 54). Still quicker gully control is obtained by transplanting a good grass sod over prepared side slopes of the gully.



GA-20035

FIGURE 54.—Complete control of erosion by 2-year-old stand of kudzu in deep, head-cutting gully in Georgia.

Various types of check dams made of woven wire, brush, loose rock, or plank are effective in reducing the gradient in the gully, and in assisting vegetation to become established. Permanent soil-saving dams of masonry, concrete, or earth are necessary in some of the largest and most stubborn gullies. These often create a pond of considerable size behind them, which may be used advantageously for stock water or other purposes. Flumes or chutes constructed of concrete, masonry, wood, or metal are sometimes used to convey runoff down the banks or overfalls of a gully. Road fills over large gullies, constructed as dams with drop-inlet culverts, have been found in some areas to be an effective means of gully control. The control of gullies has been described by Bennett (22, pp. 506-534) and Jepson (73).

The costs of gully control are affected by so many variables that averages or even the range of costs means little. Adequate treatment of some large, caving-head gullies in an advanced stage of

development may cost several thousand dollars. On the other hand, treatment of incipient field gullies may cost nothing more than the labor of the landowner in placing farm and woodland residues, and perhaps a few seeds, seedlings, or cuttings on the bare slopes.

PONDS

During the last decade the construction of small dams and ponds has been greatly accelerated in all sections of the country, especially in the Western and Midwestern States. These ponds have been built to provide a water supply for livestock, for the irrigation of small areas, for wildlife refuges, for the raising of commercial fish crops, for recreation, and for erosion control.

If small dams are substantially constructed, they form one of the most efficient means of silting control for large downstream reservoirs. Spillways should be adequate to pass the greatest runoff that is likely to occur within a 25- to 50-year period, and the capacity of the ponds should be adjusted to the size of the drainage areas to prevent their premature filling with sediment. Smaller stock ponds, involving less cost of construction, may be provided with less elaborate spillways. Ponds not only reduce channel or gully cutting in the drainageways on which they are located but also serve as points of deposition for most of the eroded material coming from their watersheds during a period of some years. Pond areas should be fenced to prevent disturbance of the surrounding soil by livestock, and vegetation should be established around the pond to prevent wave erosion and to cause the deposition of sediment in flat areas at the head of the lake.

The cost of ponds varies with the size of dams and spillways, availability of local materials, construction equipment, and cost of labor. If labor is computed on a prevailing wage basis, most farm ponds would cost from several hundred to several thousand dollars. During the last decade 2,362 conservation ponds constructed in Indiana had an average capacity of 3.4 acre-feet, and cost an average of \$772 each. In Kansas 360 larger-type ponds, having an average capacity of 45 acre-feet, cost an average of \$6,912 each. Most of these ponds were built under unemployment relief and public works programs. The average capacity of 733 ponds built on farms and range land by the Soil Conservation Service in all sections of the country was 3.86 acre-feet, and the average cost was \$616.79, or \$159.79 per acre-foot.

HIGHWAY EROSION CONTROL

The relative importance of erosion along highways, railroads, and power lines as a source of sediment reaching reservoirs has already been pointed out. Not only does the soil washed from the cuts and fills of highways contribute a considerable percentage of the total sediment produced in many watersheds, but roadside ditches and improper diversion of highway drainage often result in serious gully-ing in adjacent fields and woodlands.

Bennett has described the principal aspects of erosion control on highways (22, pp. 535-543). Extensive programs of erosion control are now being carried out by State highway agencies, especially along principal or surfaced highways. It has been found that from the practical standpoint of maintenance cost, erosion control pays for itself in a short time. Erosion-control measures have not been extended

yet, however, to most country roads, which comprise about 83 percent of approximately 3,200,000 miles of roads in the United States.

The very effective control of highway erosion achieved by many State highway departments has consisted largely of sloping and vegetating the cuts and fills and constructing substantial drains and outlets of concrete or masonry (fig. 55).

Good stands of Bermuda grass have been established in the South by broadcasting sod and fertilizer at a cost of less than \$0.02 per square yard. Where stable slopes are developed, a good cover can frequently be established by seeding to various grass mixtures. Straw mulching has been used to protect against erosion until a good grass stand is obtained. Vines, such as honeysuckle, kudzu, and Virginia creeper, have provided satisfactory protection in some parts of the East.

The costs of highway erosion control vary greatly, depending on the yardage of banks and fills to be treated. In demonstration highway projects of the Soil Conservation Service, costs have ranged from about \$500 to \$16,000 per mile of road for complete treatment.

STREAM-BANK EROSION CONTROL

Under Sources of Sediment it has been pointed out that bank cutting and bed scour of streams is in some watersheds the main source of sediment reaching points downstream.

The two principal methods of bank erosion control have been termed the blanket method and the jetty method. The blanket method involves the establishment of an effective cover of vegetation, such as a good grass sod or a stand of willow shoots along banks that have been sloped and prepared in advance. Where the lower part of a sloped and revegetated stream bank is under water long enough each year to prevent vegetative growth, this section must be riprapped with stone or protected by timber-pile jetties or other measures that will withstand the current velocities experienced. Often, as a temporary measure, brush and wire matting is used to protect the stream bank until tree growth can be established. At especially vulnerable points, such as the sharp bends, subjected to swift currents, it is at times necessary to riprap or pave the entire bank.

Effective jetties have been constructed of barriers of trees, timber piles, stone, pipe, of concrete tetrahedrons, junked automobiles, and other material. Timber piles have proved successful, both as jetties and as means of assisting in the control of especially vulnerable banks. Permeable jetties are generally more successful, as they not only slow down the velocities sufficiently to cause sediment deposition but also help stop bank erosion, whereas impermeable jetties function as dams and are more expensive and more likely to induce scouring. A very extensive literature exists on methods of bank protection, but it is based primarily on methods used on the Mississippi, Missouri, and other large streams of the country. The channel straightening and proving projects on the Los Angeles and other southern California rivers in recent years are especially notable examples of the steps taken to reduce the erosion and flooding of valuable lands bordering the channels.

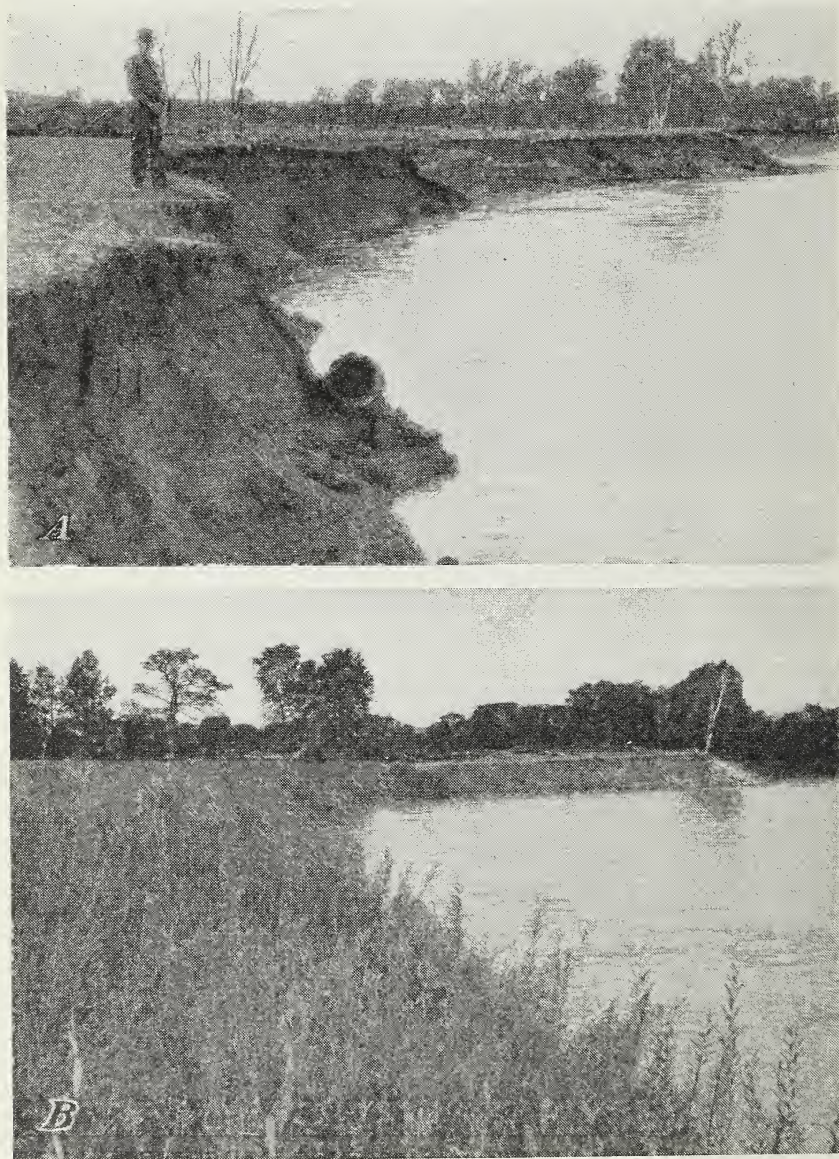
The effects of attempts to control stream-bank erosion in the drainage areas above Zuni Reservoir as a measure of silting control have already been noted (pp. 39-40). The work done by the Soil Conserva-



GA-1011-S; GA-1011-R

FIGURE 55.—A Erosion along highway ditch, resulting from improper drainage of farm land, near Buford, Ga.; B, same highway 9 months later after sloping, planting of grass, and correction of drainage.

tion Service on the Winooski River, Vt., involved treatment of 11,276 linear feet of banks at an average cost of \$2.22 per foot (fig. 56). Brush mat was placed over 10,072 square yards at a cost of \$4.49 per square yard. Floating-tree deflectors, tree barricades, and timber-pile jetties were used. Riprap and paving of 16,948 square feet cost \$0.88 per square foot.



VT. 30; VT. 30-D

FIGURE 56.—A, Bank of the Winooski River, Chittenden County, Vt., severely eroded by the 1936 flood. B, The same stream bank 2 years later. It had been sloped, planted to willows, and held with a temporary brush matting. The work was done by the Soil Conservation Service.

FLOOD PLAIN PROTECTION

Surveys by the Soil Conservation Service of the flood plains of the Ohio River, following the flood of 1937, the principal southern California rivers, following the flood of March 1938, the Connecticut and Merrimac Rivers in New England in 1938, and the Yadkin River, N. C., in 1940 have all showed convincingly that flood waters sweeping across freshly cultivated fields, where there is no obstruction to reduce velocity, will scour out large quantities of topsoil (fig. 57). This type of erosion could be controlled by planting hedgerows of tough, deep-rooted shrubs or other vegetation across the flood plain at right angles to the direction of current, spaced at intervals of a few hundred feet. The amount of land so taken up by these hedgerows would be relatively small. Hemphill (69) has suggested a method of this type.



C-8336

FIGURE 57.—Soil stripped to plow depth in Ohio River Valley by 1937 flood. On the right, bottom of plow furrows still visible in cultivated field from which 6 inches of soil was removed. On the left, the field had not been plowed, and soil was virtually undisturbed by flood waters.

WATER SPREADING

Water spreading, or flood irrigation, has been used since ancient times as a means of intercepting, diverting, and redistributing channel flow to flood-plain or lowland areas to increase soil moisture for the production of crops. As an erosion-control measure, water spreading is useful in establishing or restoring a protective cover of vegetation in areas of rainfall deficiency; and what is more important from the standpoint of reservoir protection, the water so spread is forced to drop its sediment load on the land over which it flows, thus decreasing by this amount the sediment that would be carried downstream to reservoirs.

No general standards have yet been developed for water-spreading structures. Their design is largely governed by local conditions. The spreading system must, of course, be adjusted to the expected amount and velocity of flow, the size and configuration of the area, and to the amount of sediment carried. The sediment deposited from water-spreading practices may have either a beneficial or a detrimental effect.

If the areas of water spreading are cultivated, the sediment may have the effect of enriching and fertilizing the soil. On the other hand, if water is spread on range areas, the sediment may puddle or seal the soil and smother the grass. Bennett has described the practice of water spreading (22, pp. 558-567). Taylor (116), Hemphill (69), and Faris (51) have all advocated various types of water spreading on waste flood plain and alluvial lands as a means of causing sediment deposition within the drainage basin of a reservoir, thereby controlling the rate of silting. The principle of directed flood-plain sedimentation has been described by Happ, Rittenhouse, and Dobson (65, pp. 107-109).

RESERVOIR SHORE LINE PROTECTION

Although it is known that only a very minor proportion of the sediment in most reservoirs comes from erosion of the shore line by wave action, it is nevertheless desirable, and in some cases important, to protect the shore line against this form of erosion. If the environs of the lake are used for recreation or similar purposes, shore-line erosion can become destructive both of real wealth and the esthetic appeal of the area. Shore-line protection may be achieved by practically the same methods as stream-bank control. Ordinarily vegetative plantings along the shore line are sufficient in themselves; but on steep shore lines, or where wave cutting is especially active, riprapping or some form of jetties may be required to withstand the force of waves until the vegetation can become well established.

WILDLIFE PLANTING

Wildlife plantings are made on otherwise wasted areas of land; and while they are primarily, as the name implies, to create havens for wildlife, they serve in effect to complete the erosion-control program by protecting those minor areas and spots on the farm and range that might otherwise be overlooked but that are often of critical importance in sediment production (70). Wildlife planting has been recommended for, and used on, gullied slopes and old roadways, along field borders, especially between fields and woodlands, along fence rows, on odd spots of infertile soil, along stream banks, along ditch banks and spoil banks, on marshlands, and on land temporarily retired from cultivation. The use of wildlife plantings along borders between fields and woodlands and along fence rows is especially important. It is noteworthy that each 2 miles of clean fence row represents 1 acre of wasted land. A wide variety of plants producing animal and bird feed are available and are described in publications of the Department of Agriculture (125).

BEAVER PROPAGATION

Biologists have estimated that the presettlement beaver population of the United States was 60,000,000. The dams formed by these beavers have had considerable effect in holding back sediment in some areas (72, 106). A number of biologists have advocated that beavers be reintroduced widely and protected against trapping, that the effects of their work on stream channels would have large benefits at very little cost. The use of beavers in reservoir drainage basins seems worthy of consideration.

EFFORTS IN WATERSHED EROSION CONTROL

It has been generally conceded for 50 years or more that forests have a stabilizing effect on stream flow and tend to prevent erosion and silting, thereby maintaining the navigability of streams and water supply for power, irrigation, and urban use. An act of Congress in 1897 providing for administration of the original forest reserves stated that a major purpose of the act was "securing favorable conditions of water flows." Two of the oldest of the forest reserves, now national forests, the Tonto in Arizona and the Angeles in southern California, were set aside primarily for the protection of irrigation projects and municipal water supplies. Subsequent forestry acts have emphasized the same purpose. The Weeks laws of 1911 provided for Federal cooperation with the States "for the protection of the watersheds of navigable streams" and for Federal "acquisition of lands for the purpose of conserving the navigability of navigable rivers." The Clarke-McNary law of 1924 continued the cooperation "with a view to the protection of forests and water resources" and directed that in further purchases "due consideration" be given both to watersheds of navigable streams and to those "from which water is secured for domestic use or irrigation."

Nearly 60 percent of the purchases of forest land made by the United States Forest Service since 1924 have been primarily for watershed protection. Supplementing this action by the Federal Government, municipalities have established forests that embraced 473,765 acres by 1933, largely for watershed protection. These municipal forests are generally well cared for, policed against cutting, grazing, and fire and have been extensively planted with new stock. In addition, many thousands of acres have been forested by water companies and other reservoir owners for the purpose of reservoir protection.

Among the first States to authorize acquisition of municipal forests for watershed protection were Massachusetts in 1882, New Jersey in 1906, Pennsylvania in 1909, Minnesota, New Hampshire, and Indiana in 1913, and Vermont in 1915. At even earlier dates in some of these States, towns had acquired forest lands for this purpose.

In 1933, New England contained 82,512 acres of municipal forest land; the Middle Atlantic States, 282,139 acres; the Southern States, 56,050 acres; the Central States, 30,150 acres; the Lake States, 4,660 acres; and the Rocky Mountain States, 18,254 acres, with data lacking on the Western States (*126, p. 845*). The average size of municipal forests for the country as a whole is less than 600 acres. Probably 50 percent of these forests embracing 80 percent of the acreage were acquired and developed primarily for the purpose of protecting the sources of municipal water. About 68,000 acres of the total area has been planted.

In every State in New England, some communities have acquired part of the land from which they obtain water; and where these lands have required reforestation, they have been planted (*126, p. 339*). Cities and towns in Massachusetts own more than 50,000 acres of watershed forests. Forty towns in Vermont possess municipal forests largely for watershed protection. Some 350 communities in New York own municipal forests. New York City has the largest area on its Ashokan Reservoir drainage basin. Glen Falls has planted more than 2 million trees on the denuded land acquired as a city watershed.

Newark, N. J., has a watershed forest of 35,000 acres. Private water companies also own considerable acreage of forest land. Forested municipal watersheds not only serve local public needs by yielding good water, but they have returned substantial revenues from the sale of forest products. Altogether in the region of northeastern drainages, the public owns some 5½ million acres of forest, the greater part of which may be classed as protection forests.

In Pennsylvania in 1940, 27 water companies, municipalities, and power companies planted a total of 437,000 trees for watershed protection. The largest of these operations was by the city of Altoona, which planted 211,000 trees. In the spring of 1941, 29 water and power companies planted a total of 714,500 trees. Among the large operations were Altoona with 100,000 plantings, Reading with 125,000 plantings, the Hanover Water Co. with 127,500 plantings, and the Manufacturers Water Co. of Johnstown with 111,000 plantings.

The work of the Scranton-Spring Brook Water Co., which supplies water to Scranton and the surrounding area, is a good example of the enlightened policy of many water companies in Pennsylvania. This organization owns a considerable amount of land in the drainage areas of the several reservoirs of its system. On most of these drainage areas timber was cut over before 1900 and all of the present woodland is second growth. The company owns 93 percent of the 11.5 square miles of the Stafford-Meadow Brook Watershed above Reservoir No. 5, Lake Scranton, and Williams Bridge Reservoirs. More than 600,000 trees were planted on this area between 1912 and 1928. Twenty-seven percent of the 50 square miles above No. 7 Reservoir has been purchased. About 1,000 acres have been planted with 1,500,000 trees, chiefly conifers, since 1922. A plantation has also been established on the slopes adjacent to Griffin Reservoir.

Bruce, in discussing a paper by Besley (24), stated that 25,000 trees had been planted on the 3,700 acres of drainage area of the Evitts Creek Reservoir near Cumberland, Md. E. P. Kable, general manager of the York Water Co., York Pa., in 1927, is quoted as saying that forest planting on the drainage area of the York City Reservoir increased the dry-weather runoff very materially and improved the quality of the water. Very little erosion from banks had occurred and, after a great downpour of rain, this reservoir was found to be clear, while the water from neighboring drainage areas became very turbid. The York Water Co. was reported to have planted 680,000 evergreen trees on a 700-acre tract of land owned in the watershed.

At Wilmington, Del., it has been reported (12) that a marginal strip around the 6,750-acre-foot Edgar Hoopes Reservoir had been completely reforested by trees planted on 6-foot centers in 1933 and 1934.

In the Ohio Valley region a number of progressive communities are protecting reservoir watersheds by forests (87). Akron, Ohio, began its forestation program in 1924 and now has the largest municipal forest in the State, including 2,300 acres in native forest, 600 acres planted with 500,000 trees, and 2,400 acres to be planted (1941) with 500,000 seedling trees in nursery rows. Barberton, Ohio, has planted 350,000 trees on the watershed of its reservoir since 1927 under a plan for reforesting not only the idle land, but developing a wide shelter belt of pine or spruce all around the reservoir. The Mahoning Valley

Sanitary District, which supplies water to Niles, Youngstown, and Girard, controls 4,500 acres for watershed protection and has planted 4,350,000 trees since 1931. Of these, 200,000 are hardwoods, and the remainder pine and spruce. A survival of 60 percent has been obtained in this planting. Columbus, Ohio, has planted 234,000 pine trees and 25,000 ornamental plants. Other Ohio cities that have made plantings on watersheds include Swanton, Bucyrus, Caldwell, Wellington, Crooksville, Barnesville, Norwalk, and Wellston.

In 1936, a Soil Conservation Service survey showed that Lake Decatur, constructed by Decatur, Ill., for water supply, at a cost of \$2,013,000, had lost 14.23 percent of its original capacity of 19,738 acre-feet in a little more than 14 years (62). This disclosure, and the alarm of some industrial water users, including one of the city's largest soybean processing plants, which took an option on an alternative factory site on Lake Erie, has led the city government to appropriate \$12,000 annually since 1941 to promote erosion control in the 906-square-mile watershed (91). Two soil conservation specialists were hired as full-time city employees to assist a local conservation association in the development of erosion-control measures designed to protect the life of this important reservoir. One of the objectives of the local association is "To foster rural-urban cooperation in an attack upon soil wastage. Since the loss in soil results in lower soil productivity and purchasing power, lowered land values, reservoir and stream silting, and decreased standards of living, all of which affect both farm and city people, it is important that the attack be united." The local association does not anticipate immediate results either in community improvement or in silting control, but is planning a 10-year program expected to provide fairly complete soil conservation measures on a majority of farms. In addition, the city expects to purchase some of the rough land along the lake and river and restore it to its natural cover.

Anderson and Spalding (15), in describing the history of the Springfield, Ill., water supply, note that much of the marginal land of Lake Springfield had been in cultivation prior to its purchase by the city and was devoid of trees or other vegetation. When the lake was built it seemed advisable to cover this area with trees and sod in order to protect it from erosion, as well as to add to its beauty. Sod was started all around the lake on an area of some 5,000 acres of marginal land by a liberal use of timothy and rye, as well as bluegrass and other grasses. On certain tracts to be used for residential and park purposes, evergreens and native hardwoods were planted, and certain other remote areas, unsuitable for residential use, were planted with conifers as thick as 1,000 per acre. Some of these trees had reached a height of 12 feet by 1938, and their protective influence on the soil was becoming effective through the mat of needles lying on the surface, as well as the extensive root systems underground. Most of the trees were bought as small stock 1 to 2 years old, and were placed in the city nursery for 1 to 2 years before transplanting to the lake area. About one-half million trees had been transplanted through the nursery to 1938. About half of these had survived draughts and started toward maturity. In addition, property owners around the lake were encouraged to protect their holdings against erosion, and much of the shore line was riprapped as a supplementary measure.

Fairfield, Iowa, has had considerable silting trouble with its three water-supply reservoirs (100). Its No. 3 Reservoir, which has a watershed of 2,300 acres, mostly cultivated, lost about 20 percent of its original capacity of 261 acre-feet in 10 years (1924-34). An agreement between farmers, the city of Fairfield, and the Soil Conservation Service, led to a conservation program on this watershed consisting of terracing, tree planting, and construction of silting basins at the lower end of sodded earth drainageways into which the terraces discharge. It has been estimated that the service life of No. 3 Reservoir will be extended 25 to 30 years if the conservation work is maintained, and that if it could have been applied on all the land of the watershed the life would have been increased by 50 years.

In the Southeastern States a number of reservoir owners, made aware of rapid reservoir silting by surveys of the Soil Conservation Service, have recently become much interested in watershed protection.

The Chicopee Manufacturing Co. at Gainesville, Ga., owns the entire watershed of its Chicopee Reservoir, used for water supply. It has planted all of the open land in pine trees. Most of this planting is now from 3 to 7 years old, and in 1941 the company reported that practically no sediment was being carried by the runoff into the reservoir. The company states that improvement in the reduction of sediment load occurred about 3 years after the setting of the trees, which gives some indication of the time it takes for such plantations to begin to have effect. The effectiveness in this case is due also in part to the undergrowth, such as broomsedge, which appears very rapidly when land is abandoned or when it is planted to pine in this section.

One of the most significant findings in the research studies of the Soil Conservation Service has been the effect of an integrated erosion-control program in a farming area on protection of water supplies. Sedimentation surveys were made of the municipal water-supply reservoir at High Point, N. C., in 1934, before the drainage area of this reservoir was selected as an erosion-control demonstration project of the Soil Conservation Service. In 1938, after the project was put on a maintenance basis, a second survey was made. This survey revealed that the annual sediment deposition in the reservoir after 1934 was 24 percent less than it was before this date. The annual storage loss in this 4,354 acre-foot reservoir was reduced from 0.77 percent to 0.59 percent, and the net soil loss of the drainage area was reduced from 0.93 ton to 0.71 ton per acre. This reduction took place even though hydrologic records reveal that there was at least an equal number of intense storms and a slightly higher total runoff annually after 1934 than before. This record seems even more impressive in view of the fact that only about 35 percent of the total acreage of this watershed was actually treated with erosion-control practices.

Likewise, in Texas, Oklahoma, and the Lower Mississippi Valley States, widespread interest has developed among reservoir owners during the last 5 years in watershed protection through the soil conservation program. The city of Waco, Tex., where the city reservoir of 39,378 acre-feet suffered a loss of 19.78 percent between 1930 and 1936, as shown by surveys of the Soil Conservation Service, is now actively cooperating with the soil conservation district, promoting a program for watershed protection.

Garin and Gabbard (59), in their study of reservoir sedimentation in relation to land use in Texas, took the Kaufman City Lake and its drainage area as a representative example for planning a complete conservation program designed to reduce silting to a minimum without upsetting the farming system of the drainage area. They then developed a comparison of costs and benefits for this program.

The drainage area of the Kaufman City Lake covers 1,064 acres, including the lake's surface area of 107 acres; roads, 16 acres; and farmsteads, 17 acres. The soils are principally clays and clay loams. Accelerated erosion has affected practically all of the land, although two-thirds of the area has been affected by moderate erosion, in which 25 to 75 percent of the topsoil has been removed. Occasional gullies are found on practically all of the moderately eroded fields and some of the slightly eroded fields. Most of this erosion has taken place since extensive cultivation first began about 40 years ago. This watershed is located in the transition zone between the black prairie clay soil area on the west and the sandy soil area on the east. In general appearance the watershed is similar to the Blackland prairie. It is estimated that the productivity of the land has decreased at least one-third since it was first put in cultivation.

The conservation program planned for this drainage area is as follows.

1. Cultivated land retired to pasture	acres	90
2. Cultivated land retired to meadow	do	16
3. Terraces to construct	miles	34
4. Fences to construct	feet	36,300
5. Fences to remove	do	15,675
6. Land to be sodded	acres	100
7. Overseeding of pasture	do	150
8. Linear feet of terrace-outlet sod	feet	24,000
(1) Terrace-outlet sod, 18-inch centers	acres	28
9. Linear feet of outlet channel	feet	2,000
(1) Channel excavation	cubic yards	1,600
(2) Channel sodding	square yards	4,200
10. Strip-crop seeding	acres	30
11. Strip-crop lines	miles	5
12. Terrace lines	do	37
13. Meadow seeding	acres	8

The total cost of this program has been estimated at \$5,000, an average of \$5.30 per acre.²⁴ It is estimated that after completion of this program, the average annual gross farm income, \$14.70 per acre, will increase about one-tenth, or \$1.55 per acre, almost immediately, and probably more after a few years, as compared to the continuous decline in the past. The gross annual productivity of the producing land area of 925 acres is expected to increase from \$13,600 to \$15,035 annually. On the other hand, the future annual maintenance cost would be about \$1 per acre, leaving a net farm gain of about \$510. As the past decline in value of land has been about \$485, however, and as this would be reduced by an estimated \$300, the total annual farm benefits should be \$810. If the farmers had to finance the entire program on money borrowed at 6 percent interest, and if the erosion-control practices were assumed to have an average life, with mainte-

²⁴ Per unit costs: Terrace construction, \$40 per mile; terrace lines, \$8.90 per mile; strip-crop lines, \$5 per mile; strip-crop seeding, \$2.30 per acre; pasture seeding, \$2.85 per acre; pasture sodding, \$5.10 per acre; fence removal, \$0.091 per rod; fence construction, \$0.68 per rod; meadow seeding, \$4.75 per acre; channel sodding, \$0.10 per square yard.

nance only, of 25 years, the average annual cost would be only \$391, as compared to the estimated average annual benefit of \$810. This alone would be sufficient justification for the program. In addition there are the benefits from reduced silting in Kaufman Lake.

Garin and Gabbard estimated that the proposed watershed treatment, if applied to about 90 percent of the area, would reduce the sediment inflow to the lake by about 50 percent. As a result, the useful life of the lake would be extended from 37 years with the present rate of sedimentation to 74 years with an erosion-control program. Their study indicated that the replacement cost of the reservoir would be \$34,440. The equivalent annual cost of replacement over a period of 37 years, at an interest rate of 3.5 percent, would be \$469. In addition, the annual value of lost services of the reservoir during the 37 years was estimated to be \$187, making a total annual damage of \$656.

With a control that would increase the useful life of the reservoir to 74 years, the equivalent annual cost of replacement would be only \$103. There would, however, be an increased cost of water purification during the extended life of the reservoir, amounting to an equivalent annual expense of \$128. Thus the total annual damage with the control program is estimated to be \$231; without the program, \$656. The annual reservoir benefit from the program is \$425.

In the Western States, efforts at watershed control above Zuni Reservoir have been described (pp. 39-41). As a rule, areas yielding water for sizeable cities in this region, such as Salt Lake City and Denver, are either under municipal regulation or are included in national forests. The role of vegetation is recognized in the strict supervision of all activities on the drainage areas supplying city water.

Reddick (98) has recently described a cooperative agreement between the East Bay Municipal Utility District of Oakland, Calif., and the Soil Conservation Service, designed to protect reservoirs of this organization through erosion control. The district supplies water to a population of about 500,000 in the cities and towns on the east side of San Francisco Bay. Its storage reservoirs in the hills east of Berkeley include Lake Chabot, with a drainage area of 11.75 square miles; Upper San Leandro Reservoir, 30.30 square miles; Lafayette Reservoir, 1.34 square miles; San Pablo Reservoir, 32.15 square miles; and Pinole Reservoir, 10.50 square miles—a total of 86.04 square miles of drainage area. The district has purchased and now own portions of these watersheds as follows: Lafayette, 100 percent; Chabot, 92 percent; Upper San Leandro, 45 percent; San Pablo, 56 percent; and Pinole, 24 percent. Surveys of the drainage areas have shown that the principal sources of sediment are (1) natural water courses, (2) accelerated or man-made gullies, (3) private agricultural lands, (4) landslides and slips resulting from construction of roads, buildings, and improper land use and cultural practices, as well as the character of soil, topography, and distribution of rainfall.

The program covered by this cooperative agreement provides for (1) erosion-control structures in natural waterways, gullies, and roads, (2) vegetative plantings to stabilize gullies, protect stream banks, and stabilize road banks, (3) readjustment of land uses, and (4) protection of wildlife.

The program calls for detailed planning of the area in segments of 40 to 1,000 acres. The planting of trees will be one of the principal features of the program. Though 1940, 57,000 trees were set out, in addition to 200,000 cuttings. The trees and cuttings include conifers, broad-leaf evergreens, and deciduous species. The trees are being supplied by regional nurseries of the Soil Conservation Service. Both ponds and check dams will be installed on small tributaries in the main streams. On San Pablo Creek, one large concrete dam designed to discharge flood flows up to 9,000 second-feet was recently completed.

The Tennessee Valley Authority has carried on an extensive program of reforestation, erosion control, and reservoir protection since 1933, as part of its basin-wide reservoir-storage development scheme (118). To June 30, 1941, 135 million forest-tree seedlings had been planted on more than 100,000 acres of badly eroding land. Of this number, 44 million seedlings were planted around reservoir margins. Effective fire protection is being developed.

Ritchie (101) opposed the policy of obtaining revenue from timber cutting in municipal-reservoir drainage areas in Australia. He points out that the 160 square miles of forested drainage area above the three Melbourne city reservoirs would be sufficient to serve an urban area of 1,400,000 persons. Taking the population density of a typical urban area as 15,600 persons per square mile, the proportion of forested area to densely populated area is about $1\frac{3}{4}$ acres of forest land to 1 acre of urban area. He argues that it would be the best economics to reserve 2 to 3 acres of forest area in virgin state for every acre of densely populated urban area in order to assure an undisturbed and stable water supply. He argues, furthermore, that every influence should be exerted to bring about cessation of the practice of leasing Crown lands in the mountainous forest areas for grazing purposes. It was his conviction that this was a foolish and short-sighted policy and had been responsible for more damage to the forested watershed than any other agency except fire.

PLANNING FOR WATERSHED CONTROL—AN APPRAISAL

Prior to 1935 many municipalities, water companies, and some power companies had adopted the only means then generally available to the reservoir owner in achieving erosion control, namely, purchase of much or all of the land of the drainage basin. Far from having failed to produce results, this plan seems to have given general satisfaction wherever it has been tried. Almost all reservoir owners that were foresighted enough to buy and reforest land in their drainage basins many years ago strongly advocate this policy, even where the cost of land was more than the cost of developing the storage works.

Land purchase and supervision of all activities within the drainage area, including fire control and erosion control, insure as nearly as possible the purity and stability of water supply. Although this method of control should be extended much more widely than it exists today, it must be recognized that in many sections of the United States, land should not be retired to permanent forest or grass, even if the reservoir owner were willing to meet the cost of such a policy. Our supply of highly fertile agricultural land is becoming more and more limited in relation to needs, so that large areas of good arable land cannot be permanently withdrawn from agricultural use. On

the other hand, much submarginal and infertile land, now under cultivation, which can often be purchased at nominal cost, would be ideally adapted for watershed purposes under a permanent cover of vegetation.

In cost cases the purchase of entire drainage basins by reservoir owners is financially impossible because of the high ratio of the land cost to the reservoir cost or to the service value of the reservoir.

Since 1936, a new avenue toward better watershed protection has been developing in the Nation-wide soil conservation district program (104). The Soil Conservation Act of 1935 provided that the Secretary of Agriculture might require the States to enact acceptable soil conservation laws as a condition of obtaining cooperation of the Federal Government in soil conservation activities. Copies of a model law were sent to all of the State Governors by the President in 1937. By March 15, 1944, 45 states had passed laws substantially similar to this model. Under these laws 1,007 soil conservation districts, embracing approximately 577,067,00 acres, or 30 percent of the land area of the United States, had been established (fig. 58). These districts include approximately 1,984,843 operating units and 2,593,739 farms, or nearly 43 percent of the Nation's farms. The Department of Agriculture had at that date entered into memoranda of understanding for cooperation with 931 districts covering approximately 536,291,000 acres.

These soil conservation districts are separate local units of self-government. With a few variations, the procedure for the organization and operation is as follows:

If a specified percentage of farmers in a locality wish to form a district to promote the conservation of soil and moisture resources, they may submit a petition to a State soil conservation committee. This committee then conducts public hearings in the community to determine whether a district would be feasible. If this is found to be the case, the committee calls for a referendum of all farmers and other landowners within the proposed district boundaries. If a majority votes in favor of the district, the State committee issues a certificate of organization. A board of supervisors, usually consisting of 5 members, is elected by the farmers, and constitutes the governing body of the district, with power to represent the farmers in dealing with landowners and other agencies of government. In petitioning for the organization of a district, and in all other stages of its development, the reservoir owners, as holders of land within the area, are entitled to be represented along with the farmers.

Once the district is organized, a program and work plan are developed. The program is a statement of objectives; it contains the "strategy" of the district. This strategy can and should include the protection of any reservoirs within the area against rapid loss by silting. The work plan is a statement of the methods and means to be employed in attaining the objective; it outlines the "tactics."

At this stage the district may enter into a memorandum of understanding with the Federal Department of Agriculture, under which the Department agrees to furnish the district whatever assistance it is able to render in carrying out the district work plan.

The supervisors invite farmers within the district to enter into cooperative agreements to follow a plan of conservation farm operations for a period of years, to furnish certain equipment and materials, and to perform certain operations. In return, the landowners

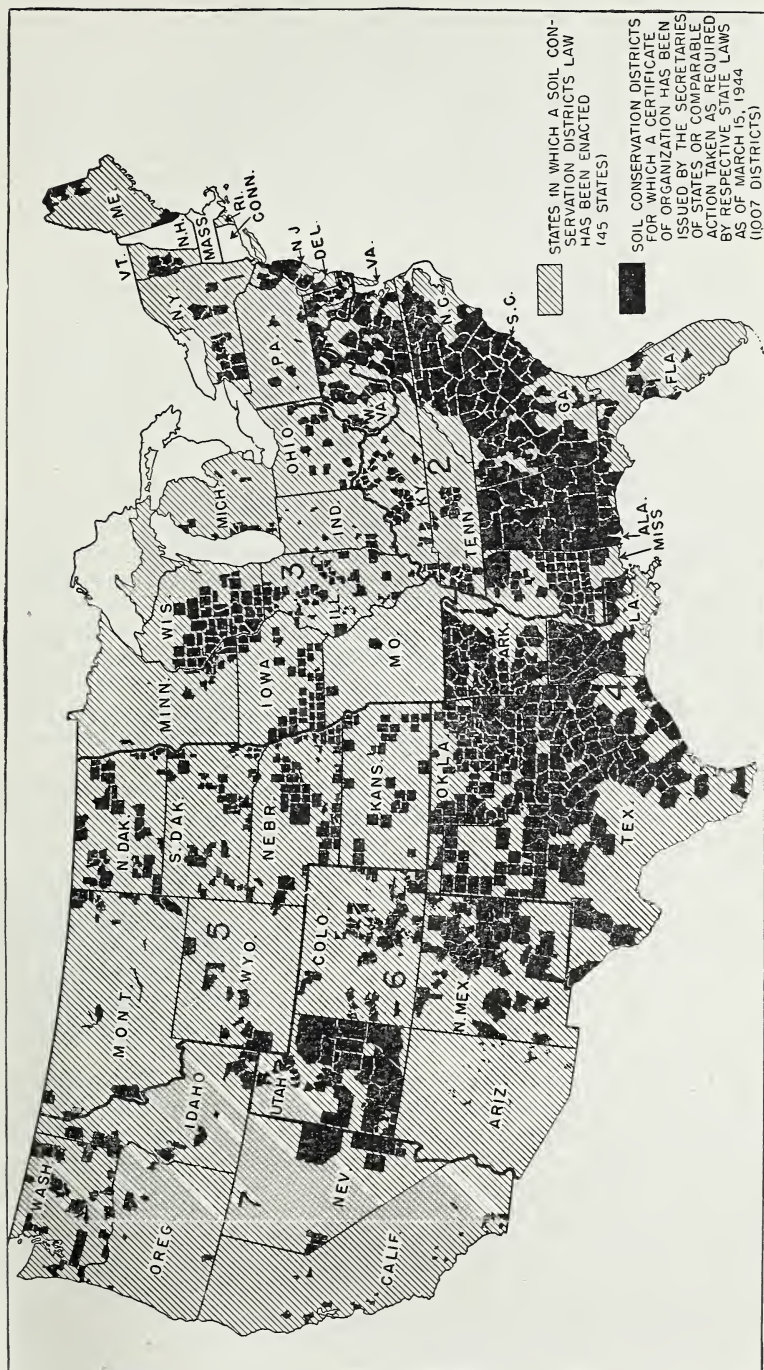


FIGURE 58.—States for which a soil conservation district law has been enacted, and soil conservation districts for which certificate of organization has been issued by the secretary of state as of March 15, 1944.

may receive certain aids from the district and other units of government. Normally, the farmer can expect the assistance of technicians of the Soil Conservation Service in developing his conservation plans, and after a plan has been accepted by the district supervisors, some assistance in putting it into practice. He may be given planting stock, fencing, or construction materials, if available, and furnished skilled supervision and labor in installing or constructing difficult structures such as terraces, dams, and diversions. Thereafter, trained soil conservationists may visit his farm regularly to see if the structures and practices are functioning properly.

The reservoir owner not only may enter into an agreement to control erosion on the lands immediately surrounding the reservoir or other lands owned within the drainage basins but may also, in consideration of the benefits received from the conservation plans carried out by the farmers at their own expense, assist through the district supervisors in the control of certain critical erosion problem areas where requirements for adequate control are beyond the means and scope of the individual landowners. Such a plan of cooperation has been proposed (32).

The assistance of the reservoir owner will be especially effective in the control of abandoned, worn-out, gullied areas that can no longer yield a profitable return to the farmer; in the control of stream-bank erosion; in the construction of interfarm drainageways and water disposal works; and in the protection of roads and other nonagricultural sources of sediment. By pooling their interests, the farmer, the reservoir owner, and the agencies of the Government can achieve the highest practicable degree of erosion control. Certainly, now is the time, while the districts are still in their formative stage, for reservoir owners to seek every means of working with them to the mutual benefit of reservoirs and the land.

It should not be understood that even the best conservation program for every acre of land will eliminate the production of sediment in the drainage area. It will not be possible to grow clean-tilled row crops on sloping land in any place, or to continue many other necessary land uses, without the expectation of some soil loss and some sediment burden in the streams. Available experimental and observational evidence indicates, however, that a control program in which every acre of land is adapted to its most prudent use might be expected in most agricultural and range-land areas, where rainfall is more than 20 inches, to reduce the sediment burden of the streams from 50 to 90 percent or more.

Ashe (16) has discussed the financial aspects of the employment of forest cover to protect reservoirs. Rodwell (103) has advocated public control of drainage areas of reservoirs supplying water for domestic use in England. Already in England, he says, the proved reduction of turbidity and enhanced purity of water drawn from afforested areas have in themselves been sufficient incentive for water authorities to embark on schemes of afforestation. Long (86) has also advocated afforestation of water-catchment areas in England, concluding that forests tend to increase locally the water supply, improve conservation, and assist in insuring purity. To these benefits he adds two further considerations, both of which may be important in this country in the post-war period. One is that afforestation can

help toward alleviating unemployment, and second, that the increasing esthetic value of the area when it is afforested generally appeals to the public of the section which it serves.

Saville (105) considers it probable that power companies may later find it economical to adopt erosion-control methods to prevent or lessen the amount of sediment now being carried by streams. He believes that such a policy would not prove unduly expensive, and that it should be considered by any company proposing to carry out a scheme of complete storage development in a drainage basin. The Tennessee Valley Authority has already adopted this far-sighted point of view.

Study of the economics of reservoir silting and soil conservation has not yet progressed to the point where watershed control can be evaluated on a general basis in comparison with other methods of silting control. Each water-storage development is a problem unto itself. Erosion control on the large drainage areas of reservoirs of low capacity-inflow ratio cannot become effective with sufficient speed or completeness to prolong greatly the reservoir's useful life. On the other end of the scale, the benefits of erosion control to many reservoirs of large capacity-inflow ratio will begin so far in the future that, according to our prevailing system of economics, only an insignificant expenditure can be justified for this or any other control method today.

The promising field for watershed control is associated primarily with those reservoirs that store between 25 and 300 acre-feet per square mile of drainage area. The greater part of this country's reservoirs fall in this class.

The greatest claim that can be made, or needs to be made, for the method of watershed control, is that it goes to the root of the problem, aiming to eliminate the cause of silting. It is primarily the surgery that removes the canker, by comparison with the palliative ointments that may keep the patient on his feet a few more years.

LITERATURE CITED

- (1) ANONYMOUS.
1877. [DESILTING OF BERNHART RESERVOIR.] (News Note) Engin. News 4: 379.
- (2) ———
1892. TROUBLE OVER RESERVOIR CLEANING. Engin. Rec. 27: 91.
- (3) ———
1912. THE WHITE RIVER POWER DEVELOPMENT IN WASHINGTON. Engin. News 67: 704-707, illus.
- (4) ———
1913. METHOD OF ESTIMATING THE PROBABLE VOLUME OF SILT DEPOSITS IN RIVER STORAGE RESERVOIRS FOR THE OKLAHOMA CITY WATER SUPPLY. Engin. and Contract 39: 290-293.
- (5) ———
1920. IMPOUNDING RESERVOIR FOR WATER SUPPLY OF OKLAHOMA CITY. Engin. News-Rec. 84: 478-479, illus.
- (6) ———
1925. VAAL RIVER BARRAGE REMARKABLE FOR ITS LARGE GATES. Engin. News-Rec. 94: 224, illus.
- (7) ———
1927. REMOVING SILT FROM RESERVOIR BY MEANS OF PORTABLE DRAGLINE. Amer. City 37: 171-172, illus.

- (8) ANONYMOUS.
1928. DÉBRIS OPENINGS BUILT IN SPILLWAY OF CALIFORNIA DAM. Engin. News-Rec. 100: 778, illus.
- (9) ———
1930. EXPERIMENTAL RESEARCHES ON THE PROCESS OF CLARIFICATION OF WATER. (Abstract) Water and Water Engin. 32: 143-144.
- (10) ———
1932. THE NIZAMSAGAR PROJECT, HYDERABAD STATE. Civ. Engin. and Pub. Works Rev. 27: 25-31, illus.
- (11) ———
1936. DREDGING OF THE BOOYSSENS SPRUIT DAM. Water and Water Engin. 38: 652, illus.
- (12) ———
1937. SILT IN WATER WORKS RESERVOIRS. Water Works Engin. 90: 45-46.
- (13) ———
1938. THREE CONCRETE ARCH DAMS FOR MINING DEBRIS CONTROL. West. Construct. News 13: 262-263, illus.
- (14) ———
1941. REMOVING RESERVOIR SILT BY SLUICING OPERATIONS. Engin. News-Rec. 127: 20, illus.
- (15) ANDERSON, S. T., and SPAULDING, C. H.
1938. MOVING THE SPRINGFIELD WATER WORKS. Amer. Water Works Assoc. Jour. 30: 585-593.
- (16) ASHE, W. W.
1926. FINANCIAL LIMITATION IN THE EMPLOYMENT OF FOREST COVER IN PROTECTING RESERVOIRS. U. S. Dept. Agr. Bul. 1430, 34 pp. illus.
- (17) BARNES, F. F., and BROWN, C. B.
1939. ADVANCE REPORT ON THE SEDIMENTATION SURVEY OF GREENBELT LAKE, GREENBELT, MARYLAND. U. S. Soil Conserv. Serv. SCS-SS-33, 12 pp. illus. [Processed.]
- (18) ——— KRAEBEL, C. J., and LAMOTTE, R. S.
1939. EFFECT OF ACCELERATED EROSION ON SILTING IN MORENA RESERVOIR, SAN DIEGO COUNTY, CALIF. U. S. Dept. Agr. Tech. Bul. 639, 21 pp., illus.
- (19) BASSELL, B.
1904. THE KERN RIVER COMPANY'S HYDROELECTRIC POWER ENTERPRISE. Engin. News 52: 55-56, illus.
- (20) BATES, C. J., and HENRY, A. J.
1928. FOREST AND STREAM-FLOW EXPERIMENT AT WAGON WHEEL GAP, COLO. FINAL REPORT ON COMPLETION OF THE SECOND PHASE OF THE EXPERIMENT. U. S. Monthly Weather Rev. Sup. 30, 79 pp., illus.
- (20a) BAUMANN, P.
1944. THE DEBRIS PROBLEM IN FLOOD CONTROL. Engin. News-Rec. 132: 40-43, illus.
- (21) BELL, H. S.
1942. STRATIFIED FLOW IN RESERVOIRS AND ITS USE IN PREVENTION OF SILTING. U. S. Dept. Agr. Misc. Pub. 491, 46 pp., illus.
- (22) BENNETT, H. H.
1939. SOIL CONSERVATION. 993 pp., illus. New York and London.
- (23) ———
1942. CONSERVING SOIL AND WATER WITH STUBBLE MULCH. Agr. Engin. 23: 37-38, 42, illus.
- (24) BESLEY, F. W.
1933. FOREST PLANTING FOR WATERSHED PROTECTION. Md.-Del. Water and Sewerage Assoc. Proc. 7: 89-96.
- (25) BHARADWAJ, B. M.
1935. PREVENTION OF SILT DEPOSITION IN CHANNELS. Indian Engin. 106: 28-29, illus.
- (26) BONNET, F.
1920. COURS DE BARRAGES. 635 pp., illus. Paris.
- (27) BOUGHTON, V. T.
1939. ENGINEERING PROBLEMS OF NEBRASKA POWER. Engin. News-Rec., 122: 723-726, illus.
- (28) BOWEN, E.
1917. CALIFORNIA RESERVOIRS SILT UP SLOWLY. Engin. News-Rec. 79: 169-170, illus.

- (29) BROWN, C. B.
1937. PROTECTING BOTTOMLANDS FROM EROSIONAL DEBRIS: A CASE HISTORY. U. S. Soil Conserv. Serv., Soil Conserv. 3: 93-96, illus.
- (30) ———
1941. DYNAMICS OF ENTRAINMENT OF EROSIONAL DEBRIS AND SEDIMENTATION. Amer. Geophys. Union Trans. 22 (2): 305-315, illus.
- (31) ———
1941. FACTORS IN CONTROL OF RESERVOIR SILTING. Amer. Water Works Assoc. Jour. 33: 1022-1040, illus.
- (32) ———
1941. PROTECTING RESERVOIR WATERSHEDS THROUGH THE DISTRICTS PROGRAM. U. S. Soil Conserv. Serv., Soil Conserv. 6: 230-232, illus.
- (33) ———
1941. SILT TAKES HEAVY STORAGE TOLL. Water Works Engin. 94: 874-877 illus.
- (34) ——— AND BARNES, F. F.
1936. ADVANCE REPORT ON THE SEDIMENTATION INVESTIGATIONS OF RESERVOIR AND NAVIGATION IMPROVEMENTS ON THE NEW RIVER, VIRGINIA AND WEST VIRGINIA. U. S. Soil Conserv. Serv. SCS-SS-6, 24 pp., illus. [Processed.]
- (35) BRYAN, K.
1941. PRE-COLUMBIAN AGRICULTURE IN THE SOUTHWEST, AS CONDITIONED BY PERIODS OF ALLUVIATION. Amer. Geog. Assoc. Ann. 31: 219-242, illus.
- (36) BUCKLEY, R. B.
1905. THE IRRIGATION WORKS OF INDIA. Ed. 2, 336 pp., illus. London and New York.
- (37) CALMELS, M.
1881. SUR LE DÉVASEMENT DES BARRAGES-RÉSEROIRS EN ALGÉRIE AU MOYEN DE LA FORCE MOTRICE DES EAUX DU BARRAGE ET L'AIR COMPRIMÉ, [ON SILT REMOVAL FROM THE STORAGE-RESERVOIRS IN ALGERIA BY MEANS OF THE MOTIVE FORCE OF WATER FROM THE DAM AND OF COMPRESSED AIR.] Assoc. Franç. pour l'Avanc. des Sci. Compt. Rend. 10: 243-251, illus.
- (38) CAMPBELL, W. M.
1927. THE WATER SUPPLY OF DURBAN, NATAL. Water and Water Engin. 29: 349-351, illus.
- (39) CLEARY, J. B.
1930. SILT PROBLEM IN RELATION TO INTERMITTENT STREAM BED RESERVOIRS. Wyo. Engin. Soc. Proc. 11: 50-55, illus.
- (40) CRADDOCK, G. W., and PEARSE, C. K.
1938. SURFACE RUN-OFF AND EROSION OF GRANITIC MOUNTAIN SOILS OF IDAHO AS INFLUENCED BY RANGE COVER, SOIL DISTURBANCE, SLOPE, AND PRECIPITATION INTENSITY. U. S. Dept. Agr. Cir. 482, 24 pp., illus.
- (41) DARE, H. H.
1928. BURRINJUCK DAM, MURRUMBIDGEE RIVER. Austral. Inst. Engin. Trans. 9: 1-23.
- (42) DAVIS, A. P.
1897. IRRIGATION NEAR PHOENIX, ARIZONA. U. S. Geol. Survey Water Supply Paper, 2, 98 pp., illus.
- (43) ———, and WILSON, H. M.
1919. IRRIGATION ENGINEERING. 617 pp., illus. New York.
- (44) D'ROHAN, W.
1911. THE SILTING UP OF RESERVOIRS AND CANALS AND SOME METHODS FOR PREVENTING SAME. Engin. and Contract, 35: 56-58, illus.
- (45) EAKIN, H. M.
1939. SILTING OF RESERVOIRS. U. S. Dept. Agr. Tech. Bul. 524, rev. by C. B. Brown, 168 pp., illus.
- (46) EATON, E. C.
1936. FLOOD AND EROSION CONTROL PROBLEMS AND THEIR SOLUTION. Amer. Soc. Civ. Engin. Trans. 101: 1302-1330, illus.
- (47) EDGEcombe, A. R. B.
1934. REPORT ON THE SILTING OF RESERVOIRS AND MEASURES TAKEN OR PROJECTED FOR ITS PREVENTION OR CONTROL. (United Provinces, India.) 36 pp., illus. Allahabad.

- (48) ELLIS, M. M.
1940. WATER CONDITIONS AFFECTING AQUATIC LIFE IN ELEPHANT BUTTE RESERVOIR. U. S. Bur. Fisheries Bul. 34: 257-304, illus.
- (49) ELLIS, J. W.
1913. CLEANING A LARGE SETTLING RESERVOIR. Engin. Rec. 67: 689-691, illus.
- (50) EVANS, L.
1920. SILT DISPOSAL AT TACOMA HYDE-ELECTRIC PLANT. Power 51: 694-697, illus.
- (51) FARIS, O. A.
1933. THE SILT LOAD OF TEXAS STREAMS. U. S. Dept. Agr. Tech. Bul. 382, 70 pp., illus.
- (52) FLOCK, L. R.
1934. RECORDS OF SILT CARRIED BY THE RIO GRANDE AND ITS ACCUMULATION IN ELEPHANT BUTTE RESERVOIR. Amer. Geophys. Union Trans. 15 (2): 468-473.
- (53) FOLLETT, W. W.
[1913.] SILT IN THE RIO GRANDE. (U. S. Dept. of State, Internatl. Boundary Comm. and Comm. for the Equitable Distribution of the Waters of the Rio Grande, United States and Mexico.) 102 pp. [Washington, D. C.]
- (54) FORESTER, D. M.
1938. THE DESILTING WORKS AT IMPERIAL DAM. U. S. Bur. Reclam., Reclam. Era 28: 152-156, illus.
- (55) FRANK, B.
1941. HEADWATER HIGHWAYS—A NEW FOREST MENACE. Jour. Forestry 39: 291-296.
- (56) FRONTINUS, S. J.
1899. THE WATER SUPPLY OF THE CITY OF ROME. Transl. by C. Herschel. 296 pp., illus. Boston.
- (57) GARIN, A. N.
1941. ADVANCE REPORT ON THE ECONOMIC EFFECTS OF PREDICTED SEDIMENTATION IN MORRIS SHEPPARD LAKE, TEXAS. U. S. Soil Conserv. Serv. SCS-EC-3, 18 pp., illus. [Processed.]
- (58) ———, and FORESTER, G. W.
1940. EFFECT OF SOIL EROSION ON THE COSTS OF PUBLIC WATER SUPPLY IN THE NORTH CAROLINA PIEDMONT. U. S. Soil Conserv. Serv. SCS-EC-1, 106 pp., illus. [Processed.]
- (59) ———, and GABBARD, L. P.
1941. LAND USE IN RELATION TO SEDIMENTATION IN RESERVOIRS, TRINITY RIVER BASIN, TEXAS. Tex. Agr. Expt. Sta. Bul. 597, 65 pp., illus.
- (60) GILBERT, G. K.
1917. HYDRAULIC-MINING DEBRIS IN THE SIERRA NEVADA. U. S. Geol. Survey Prof. Paper 105, 154 pp., illus.
- (61) GLENN, L. C.
1911. DENUDATION AND EROSION IN THE SOUTHERN APPALACHIAN REGION AND THE MONONGAHELLIA BASIN. U. S. Geol. Survey Prof. Paper 72, 137 pp., illus.
- (62) GLYPH, L. M., JR., and JONES, V. H.
1937. ADVANCE REPORT ON THE SEDIMENTATION SURVEY OF LAKE DECATUR, DECATUR, ILLINOIS. U. S. Soil Conserv. Serv. SCS-SS-12, 23 pp., illus. [Processed.]
- (63) GOTTSCHALK, L. C.
1942. SEDIMENTATION INVESTIGATION OF CARNEGIE LAKE, PRINCETON, N. J. U. S. Soil Conserv. Serv. Spec. Rpt. 1, 5 pp. [Processed.]
- (64) GROVER, N. C., and HOWARD, C. S.
1938. THE PASSAGE OF TURBID WATER THROUGH LAKE MEAD. Amer. Soc. Civ. Engin. Trans. 103: 720-790, illus.
- (65) HAPP, S. C., RITTENHOUSE, G., and DOBSON, G. C.
1940. SOME PRINCIPLES OF ACCELERATED STREAM AND VALLEY SEDIMENTATION. U. S. Dept. Agr. Tech. Bul. 695, 133 pp., illus.
- (66) HARDY, E. D.
1911. WATER PURIFICATION PLANT, WASHINGTON, D. C., RESULTS OF OPERATION. Amer. Soc. Civ. Engin. Trans. 72: 301-402, illus.

- (67) HARISBERGER, J.
1916. SOLIDS A PROBLEM AT POWER PLANTS IN NORTHWEST. *Engin. Rec.* 74: 290-291, illus.
- (68) HEINLY, B. A.
1910. MAKING A STREAM EXCAVATE ITS OWN RESERVOIR. *Munic. Engin.* 39: 10-12, illus.
- (69) HEMPHILL, R. G.
1931. SILTING AND LIFE OF SOUTHWESTERN RESERVOIRS. *Amer. Soc. Civ. Engin. Trans.* 95: 1060-1072.
- (70) HOLT, E. G., and VAN DERSAL, W. R.
1942. WILDLIFE AND LAND USE PATTERNS. U. S. Dept. Agr. Misc. Pub. 444, 73 pp., illus.
- (71) HOUGH, J. L., and FLAXMAN, E. M.
1938. ADVANCE REPORT ON THE SEDIMENTATION SURVEY OF THE BENNETT IRRIGATION AND SILTING BASIN, WILSON CREEK, WASHINGTON. U. S. Soil Conserv. Serv. SCS-SS-27, 20 pp., illus. [Processed.]
- (72) IVES, R. L.
1942. THE BEAVER-MEADOW COMPLEX. *Jour. Geomorph.* 5: 191-203, illus.
- (73) JEPSON, H. G.
1939. PREVENTION AND CONTROL OF GULLIES. U. S. Dept. Agr. Farmers' Bul. 1813, 59 pp., illus.
- (74) JOHNSON, J. W.
1942. UNDERFLOW STUDIES AT LAKE ISSAQUEENA. *Civ. Engin.* 12: 513-516, illus.
- (75) ———, and BROWN, H. A.
1941. PRINCIPLES AFFECTING THE CONTROL OF EROSION IN ROAD CUTS AND ROADSIDE DITCHES. U. S. Soil Conserv. Serv., Soil Conserv. 7: 138-140, illus.
- (76) JONES, V. H.
1938. ADVANCE REPORT ON THE SEDIMENTATION SURVEY OF MISSION LAKE, HORTON, KANSAS. U. S. Soil Conserv. Serv. SCS-SS-22, 15 pp., illus. [Processed.]
- (77) JORDANA, J.
1925. EL PANTANO DE LA PEÑA EN 1924. [THE PEÑA RESERVOIR IN 1924.] *Rev. de Obras Púb.* 73: 39-42.
- (78) KANTHACK, F. E.
1924. THE PRINCIPLES OF IRRIGATION ENGINEERING—WITH SPECIAL REFERENCE TO SOUTH AFRICA. 299 pp., illus. London.
- (79) KRESNIK, P.
1890. MEASURES ADOPTED FOR THE SAFETY AND SERVICE OF RESERVOIR DAMS. (Abstract) *Engin. News* 23: 435-436.
- (80) LABELLE, H. F.
1908. SILTING UP OF RESERVOIRS. *Engin. News* 60: 211-212.
- (81) LATHROP, T. R.
1941. REFORESTATION OF OHIO WATER WORKS PROPERTIES. *Amer. Water Works Assoc. Jour.* 33: 1175-1178.
- (82) LAWSON, L. M.
1919. MOVEMENT OF SILT, ELEPHANT BUTTE RESERVOIR. *Reclam. Rec.* 10: 411.
- (83) LAZEAR, R. W.
1918. REMOVING SILT FROM IRRIGATION RESERVOIR WITH DRAGLINE EXCAVATOR. *Munic. and County Engin.* 55: 115, illus.
- (84) LEWIS, A. D.
1936. SILTING OF FOUR LARGE RESERVOIRS IN SOUTH AFRICA. 2d Cong. on Large Dams, Washington, D. C., *Commun.* 5: 177-201, illus.
- (85) LIPPINCOTT, J. B.
1900. STORAGE OF WATER ON GILA RIVER, ARIZONA. U. S. Geol. Survey Water-Supply Paper 33, 98 pp., illus.
- (86) LONG, A. P.
1936. THE AFFORESTATION OF WATER CATCHMENT AREAS. *Water and Water Engin.* 36: 412-414.
- (87) LOS ANGELES COUNTY FLOOD CONTROL DISTRICT.
1941. ANNUAL REPORT ON HYDROLOGIC DATA: SEASON 1930-40. 221 pp. illus. Los Angeles.

- (88) MATHEWSON, T. K.
1934. SAND TRAPS IN A POWER CANAL. *Civ. Engin.* 4: 599, illus.
- (89) MEYERS, A. A.
1912. OVER DE SLIBKWESTIE BIJ DALAFSLUITINGEN [ON THE SILT QUESTION IN IMPOUNDING RESERVOIRS]. *K. Inst. van Ingen. Afd. Ned-Indië, Tijdschr. Afl. III, blz. 1.* [In Dutch. Original not available in the United States. Translation supplied by J. C. Stevens, Consulting Engineer, Portland, Oregon. Title from Index of Publications of Institute.]
- (90) MORTIMORE, M. E.
1941. A DOUBLE CHECK ON EROSION. *U. S. Soil Conserv., Soil Conserv.* 7: 150-151, illus.
- (91) MUSSER, R. H.
1942. A FARM-CITY PLAN FOR EROSION CONTROL. *Jour. Land and Pub. Util. Econ.* 18: 323-327.
- (92) NAGLE, J. C.
1902. THE SILT PROBLEM IN CONNECTION WITH IRRIGATION STORAGE RESERVOIRS. *Tex. Acad. Sci. Trans.* 4 (2): 33-46.
- (93) NEWELL, R. J.
1924. SAND TRAP PREVENTS SILTING OF CANAL. *Engin. and Contract.* 62: S10-S11, illus.
- (94) NORTON, E. A.
1939. SOIL CONSERVATION SURVEY HANDBOOK. *U. S. Dept. Agr. Misc. Pub.* 352, 39 pp., illus.
- (95) ORTH, F.
1934. DIE VERLANDUNG VON STAUBECKEN [THE SILTING OF RESERVOIRS]. *Bautechnik.* 12: 345-358, illus.
- (95a) PARKER, P. A. M.
1932. THE CONTROL OF WATER. Ed. 2, 1055 pp., illus. London.
- (96) PARSHALL, R. L.
1934. THE REMOVAL OF BED LOAD FROM ARTIFICIAL CHANNELS. *Amer. Geophys. Union Trans.* 15 (2): 603-606.
- (97) PENNSYLVANIA STATE PLANNING BOARD.
1937. DRAINAGE BASIN STUDY OF PENNSYLVANIA, PART 1, DELAWARE, LEHIGH AND SCHUYLKILL RIVERS. *Pa. State Planning Board Pub.* 10: 79-111.
- (98) REDDICK, H. E.
1941. EROSION CONTROL FOR RESERVOIR PROTECTION. *U. S. Soil Conserv. Serv., Soil Conserv.* 7: 77-79, illus.
- (99) REED, O.
1931. SWISS METHODS OF AVOIDING SILT DEPOSITS IN RESERVOIRS. *Engin. News-Rec.* 107: 289-290, illus.
- (100) REICHSTEIN, A.
1941. SOIL CONSERVATION HELPS TO PROTECT WATER SUPPLY. *Pub. Works* 73 (12): 33-35, illus.
- (101) RITCHIE, E. G.
1923. FORESTS IN RELATION TO WATER CONSERVATION. *Austral. Forestry Jour.* 6: 89-95.
- (102) ROBINSON, H. F.
1920. THE SILT PROBLEM OF THE ZUNI RESERVOIR. *Amer. Soc. Civ. Engin. Trans.* 83: 868-893, illus.
- (103) RODWELL, J. A.
1936. PRE-STORAGE PROBLEMS. *Water and Water Engin.* 38: 377-384, illus.
- (104) RULE, G. K.
1941. SOIL CONSERVATION DISTRICTS IN ACTION ON THE LAND. *U. S. Dept. Agr. Misc. Pub.* 448, 25 pp., illus.
- (105) SAVILLE, T.
1924. WATER-POWER INVESTIGATION OF DEEP RIVER. *N. C. Geol. and Econ. Survey, Econ. Paper* 54, 43 pp., illus.
- (106) SCHEFFER, P. M.
1938. THE BEAVER AS AN UPSTREAM ENGINEER. *U. S. Soil Conserv. Serv., Soil Conserv.* 3: 178-181, illus.
- (107) SCHOKLITSCH, A.
1935. STAURAUMLERLANDUNG UND KOLKABWEHR [THE SILTING OF RESERVOIRS AND SCOUR PREVENTION]. 178 pp., illus. Vienna.

- (108) SCHUYLER, J. D.
1901. RESERVOIRS FOR IRRIGATION, WATER POWER, AND DOMESTIC WATER SUPPLY. 414 pp., illus. New York.
- (109) SEIGFRIED, J. H.
1927. SILT DEPOSITS AND METHODS OF ELIMINATION. Northwest Elect. Light and Power Assoc., Tech. Sec. Proc. 4 : 113-120, illus.
- (110) SERGAEV, M. S.
1932. [CLEANING OF SILTED RESERVOIRS.] Sci. Res. Inst. Hydrotech. Trans. 8: 148-153. (In Russian.)
- (111) SIMAIKA, Y. M.
1940. THE SUSPENDED MATTER IN THE NILE. Egypt Min. Pub. Works, Phys. Dept. Paper 40, 70 pp., illus.
- (112) SISLER, J. D., FRASER, T. and ASHMEAD, D. C.
1928. ANTHRACITE CULM AND SILT. Pa. Geol. Survey, Ser. 4, Bul. M-12, 268 pp., illus.
- (113) STEVENS, J. C.
1936. THE SILT PROBLEM. Amer. Soc. Civ. Engin. Trans. 101 : 207-288, illus.
- (114) STRANGE, W. L.
1928. INDIAN STORAGE RESERVOIRS WITH EARTHEN DAMS. Ed. 3, 498 pp., illus. London.
- (115) SUTHERLAND, R. A.
1935. FRENCH BUILD HIGH DAM IN NARROW LIMESTONE CANYON. Engin. News-Rec. 115 : 706-709, illus.
- (116) TAYLOR, T. U.
1929. SILTING OF THE LAKE AT AUSTIN, TEXAS. Amer. Soc. Civ. Engin. Trans. 93 : 1681-1735, illus.
- (117) ———
1930. SILTING OF RESERVOIRS. Tex. Univ. Bul. 3025, 170 pp., illus.
- (118) TENNESSEE VALLEY AUTHORITY.
[1942.] ANNUAL REPORT OF THE TENNESSEE VALLEY AUTHORITY 1941. 289 pp., illus. Washington.
- (119) ———, CORPS OF ENGINEERS, DEPARTMENT OF AGRICULTURE, and others.
1940-41. A STUDY OF METHODS USED IN MEASUREMENT AND ANALYSIS OF SEDIMENT LOADS IN STREAMS. 5 pts., illus. (Pts. 6-9 in press.) Iowa City.
- (120) TOWL, R. N.
1924. HANDLING SILT IN SETTLING BASINS. Engin. and Contract. 62: 341-344, illus.
- (121) TROXELL, H. C., and PETERSON, J. Q.
1937. FLOOD IN LA CAÑADA VALLEY, CALIFORNIA. U. S. Geol. Survey Water-Supply Paper 796-C: 53-98, illus.
- (122) UNITED STATES CONGRESS.
1935. AN ACT TO PROVIDE FOR THE PROTECTION OF LAND RESOURCES AGAINST SOIL EROSION, AND FOR OTHER PURPOSES. 74th Cong., 1st sess., Pub. 46 [H. R. 7054], 2 pp.
- (123) UNITED STATES CORPS OF ENGINEERS, U. S. ARMY.
1914. SAN CARLOS IRRIGATION PROJECT, ARIZONA. (Letter from the Secretary of War transmitting a report of a Board of Engineer Officers, U. S. Army . . .) 63d Cong., 2d sess., House Doc. 791, 168 pp., illus.
- (124) ———
1931. MANISTEE RIVER, MICH. (Letter from the Secretary of War transmitting report from the Chief of Engineers . . .) 72d Cong., 1st sess., House Doc. 159, 51 pp., illus.
- (125) UNITED STATES DEPARTMENT OF AGRICULTURE.
1942. LIST OF AVAILABLE PUBLICATIONS OF THE UNITED STATES DEPARTMENT OF AGRICULTURE, U. S. Dept. Agr. Misc. Pub. 60, 227 pp.
- (126) UNITED STATES FOREST SERVICE.
1933. A NATIONAL PLAN FOR AMERICAN FORESTRY. (Letter from the Secretary of Agriculture transmitting . . . a report of the Forest Service . . .) 73d Cong., 1st sess., Sen. Doc. 12, 2 v., illus.
- (127) ———
1936. THE WESTERN RANGE. (Letter from the Secretary of Agriculture . . .) 74th Cong., 2d sess., Sen. Doc. 199, 620 pp., illus.

- (128) UNITED STATES FOREST SERVICE AND SOIL CONSERVATION SERVICE.
1940. INFLUENCES OF VEGETATION AND WATERSHED TREATMENTS OF RUN-OFF, SILTING, AND STREAM FLOW, A PROGRESS REPORT OF RESEARCH. U. S. Dept. Agr. Misc. Pub. 397, 80 pp., illus.
- (129) UNITED STATES RECLAMATION SERVICE.
1903. FIRST ANNUAL REPORT OF THE RECLAMATION SERVICE, 1902. 57th Cong., 2d sess., House Doc. 79, 317 pp., illus.
- (130) ————
1905. THIRD ANNUAL REPORT OF THE RECLAMATION SERVICE, 1903-04. Ed. 2, 58th Cong., 3d sess., House Doc. 28, 653 pp., illus.
- (131) VOGT, A.
1927. SCHLAMMTRANSPORT DURCH SCHWIMMENDE HEBER-BAGGER [SEDIMENT TRANSPORTATION BY MEANS OF A FLOATING LIFT-DREDGER]. Forder-
tech. u. Frachtverkehr 20: 454-457, illus.
- (132) WEGEMANN, E.
1927. THE DESIGN AND CONSTRUCTION OF DAMS. Ed. 8, 740 pp., illus. New York and London.
- (133) WHITMAN, E. B.
1914. THE NEW LOCH RAVEN DAM AT BALTIMORE, MARYLAND. Engin. News 72: 331-337, illus.
- (134) WIEBE, A. H.
1939. DENSITY CURRENTS IN NORRIS RESERVOIR. Ecology 20: 446-450, illus.
- (135) WILSON, H. M.
1893. AMERICAN IRRIGATION ENGINEERING. U. S. Geol. Survey Ann. Rpt. 13 (pt. 3): 101-349.
- (136) ————
1903. IRRIGATION IN INDIA (SECOND EDITION). U. S. Geol. Survey Water-Supply Paper 87, 238 pp., illus.
- (137) WINSOR, L. M.
1933. THE BARRIER SYSTEM FOR CONTROL OF FLOODS IN MOUNTAIN STREAMS. U. S. Dept. Agr. Misc. Pub. 165, 24 pp., illus.
- (138) WOOD, G. L.
1928. AUSTRALIAN FORESTS IN RELATION TO CLIMATE AND EROSION. Austral. Forestry Jour. 11: 131-138, illus.

INDEX

	Page		Page
Afforestation, effect on erosion	128-132	Caballo Dam, N. Mex.	30
Agua Caliente Dam, Calif.	36	California	8
Alabama	21, 68	19-20, 35-36, 42, 44, 54, 56, 84, 95-97,	
Algeria	27, 89-90, 102-103, 111	103-104, 108, 111, 118-120, 123, 126-	
Alicante Dam, Spain	100-102	128, 132, 147, 152-153.	
Altoona, Pa.	8, 84, 148	Camperdown Reservoir, So. Africa	61
American River, Calif.	45-46, 103	Canals, bypass	58-64
Amsteg Reservoir, Switzerland	63	Capacity, useful	19
Arizona	8	Capacity-watershed ratio	25-29
27, 29-30, 58, 62-63, 65-74, 86, 93,		Carnegie Lake, N. J.	93
106-109, 147.		Channelway protection	138
Arkansas River, Colo.	19, 52	Check dams	140
Ashokan Reservoir, N. Y.	147	Chicopee Reservoir, Ga.	150
Aswan Dam, Egypt	79-81, 105	Cincinnati, Ohio, reservoirs	112
Austin Dam, Tex.	8, 25	Clarinda, Iowa, Conservation Experi-	
Australia	82, 122, 153	ment Station	116
Austria	82	Cold Springs Reservoir, Oreg.	52
Baltimore Reservoir, Tex.	52	Conduits, bypass	58-64
Baltimore, Md.	8, 68, 87	Colorado	19, 52, 84, 121, 152
Bear River, Calif.	44, 104	Colorado River of the West	54, 116
Beaver propagation	146	Colorado River, Tex.	8, 25, 27
Bennett Desilting Basin, Wash.	34, 41	Conservation surveys	23
Bernhart Reservoir, Pa.	84	Construction, effect on silting	126
Bhatgarh Dam, India	76-79, 105	Coon Creek, Wis.	117
Big Tujunga Reservoir, Calif.	95-96	Cordell Reservoir, Okla.	85
Booyen Spruit Reservoir, So. Africa	87	Costs of—	
Boulder Dam, Nev.-Ariz.	27, 65-74	dredging	93
Bridgeport Reservoir, Tex.	25, 27	forestation	130-132
Buena Vista Reservoir, Calif.	111	flushing	95
Buffalo, N. Y., harbor	116	grass seeding	133
Burma	50	reservoirs	3-6
Burning, effect on erosion	118-121	reservoir silting	21
Burrinjuck Reservoir, Australia	82	water filtration	17

	Page		Page
Cover crops-----	135	Lake Issaqueena, S. C.-----	67-69, 71, 118, 125
Crop rotation-----	134	Lake Kemp, Tex.-----	50
Cultivation-----	124-125	Lake McMillan, N. Mex.-----	9, 48-50
contour-----	135	Lake Mead, Nev.-Ariz.-----	27, 65-74
practices-----	133-138	Lake Murray, S. C.-----	70
Dalecarlia Reservoir, D. C.-----	53	Lake Osborne, Kans.-----	25
Dam, raising-----	29-31	Lake Overholser, Okla.-----	59-61
Debris basins-----	32-47, 51	Lake Roland, Md.-----	8, 87
Deep River, N. C.-----	15, 85, 97-98, 110	Lake Scranton, Pa.-----	148
Deforestation, effect on erosion-----	121-122	Lake Springfield, Ill.-----	149
Delaware-----	148	Lake Tapps, Wash.-----	56
Density currents-----	64-74	Lake Waco, Tex.-----	25, 77
Devils Gate Reservoir, Calif.-----	84	Lake Whiting, India.-----	76, 77
Djidionia Reservoir, Algeria-----	89-90	Land use, effects on erosion-----	118-128
Doniphan County Debris Basin, Kans.-----	45-46	La Peña Reservoir, Spain-----	82
Draining-----	94-98	Lexington Reservoir, N. C.-----	115, 125
Dredging-----	86-94	Little La Crosse River, Wis.-----	117
East Bay Municipal Utilities District, Calif.-----	8, 152	Little Sioux Watershed, Iowa-----	116
Echo Reservoir, Utah-----	67	Lloyd Dam, India-----	76, 79
Edgar Hoopes Reservoir, Del.-----	148	Loch Raven Reservoir, Md.-----	8, 68, 88
Egypt-----	79-81, 105	Logging, effect on erosion-----	121-122
Elche Dam, Spain-----	100	Los Angeles, Calif.-----	19-20, 42, 84, 97, 108, 111
Elephant Butte Reservoir, N. M.-----	8-9, 18, 27, 29, 30, 61-62, 66, 68, 70, 93, 106, 116	Los Angeles County Flood Control District-----	32, 42, 84, 95
England-----	41, 156	Loup River Public Power District, Nebr.-----	55-56
Enoree River, S. C.-----	74	Lower Salt Creek Reservoir, Wyo.-----	103
Erosion Control-----	113-157	Lower San Fernando Reservoir, Calif.-----	108
Evaporation, effect of silting on-----	29	Lozoya Reservoir, Spain-----	112
Evitts Creek Reservoir, Md.-----	148	McKay Reservoir, Oreg.-----	52
Fairfield, Iowa, reservoirs-----	150	Mahoning Valley Sanitary District, Ohio-----	132, 148
Fairmount Dam, Pa.-----	127	Maryland-----	8, 31-32, 53, 68, 87-88, 126, 148
Federated Malay States-----	50	Massachusetts-----	147
Filtration of water-----	17	Medina Reservoir, Tex.-----	97-98
Flood Plains, protection of-----	145	Miami Conservancy District, Ohio-----	19, 83
Flushing-----	94-98	Michigan-----	122
Folsom Dam, Calif.-----	103-104	Middle Rio Grande Conservancy District, N. Mex.-----	50
Forest management-----	128-132	Mining debris, effect on silting-----	127
France-----	27-28	Minnesota-----	147
Georgia-----	21, 150	Mission Lake, Kans.-----	37-38
Gibraltar Reservoir, Calif.-----	35-36, 120	Mississippi-----	28, 115, 125
Gila River, Ariz.-----	8, 27, 30, 58, 62-63, 86, 93, 106-109	Missouri-----	28, 46
Grassland management-----	132-133	Missouri River-----	45, 118
Greenbelt Lake, Md.-----	126	Mono Debris Dam, Calif.-----	35
Griffin Reservoir, Pa.-----	148	Montana-----	128
Gullies, erosion and control of-----	115, 138-141	Morena Reservoir, Calif.-----	123
Habra Reservoir, Algeria-----	102-103	Morris Shepard Reservoir, Tex.-----	21
Haines Canyon Debris Basin, Calif.-----	84	Mulching-----	134
Hamiz Reservoir, Algeria-----	103	Mundaring Reservoir, Australia-----	122
High Point Reservoir, N. C.-----	150	Muskingum Watershed Conservatory District, Ohio-----	28
Highways, erosion and control of-----	125	Nebraska-----	46, 55-56
Hill Creek Desilting Basin, Nebr.-----	46	New Hampshire-----	147
Holt Creek Reservoir, Pa.-----	127	New Jersey-----	93, 147, 148
Horse Creek Reservoir, Colo.-----	52-53	New Mexico-----	8-9, 18, 21, 27, 29-30, 34, 39-40, 48-50, 61-62, 66, 68, 70-71, 93, 103, 106-109, 116, 142, 152
Idaho-----	57, 130	New York-----	84, 116, 147
Illinois-----	117, 149	Nevada-----	27, 65-74
Imperial Dam, Calif.-Ariz.-----	54	Nile River, Egypt-----	79-80
India-----	22, 28, 57, 76-79, 105	Nizamsagar Dam, India-----	28
Indiana-----	141, 147	Norris Reservoir, Tenn.-----	28, 68
Iowa-----	46, 116-117, 150	North Carolina-----	15, 21, 85, 93, 97-98, 110, 115, 125, 127, 145, 150
Italy-----	33	Nutria Dam, N. Mex.-----	40
John Martin Reservoir, Colo.-----	19	Ohio-----	19, 28, 112, 131, 148-149
Kansas-----	25, 37-38, 45-46, 141	Ohio River-----	106, 145
Kaufman City Lake, Tex.-----	151-152	Oklahoma-----	59-61, 85
Kern River, Calif.-----	56	Oregon-----	52
Kittanning Reservoir, Pa.-----	8, 84	Organic matter, effect on soil loss-----	134
La Crosse, Wis., Conservation Experiment Station-----	117, 124	Outlet works-----	31
Lafayette Reservoir, Calif.-----	152	Overgrazing, effect on erosion-----	122-124
Lake Arthur Reservoir, So. Africa-----	67	Pecos River, N. Mex.-----	9, 21, 48-50
Lake Austin, Tex.-----	8, 25	Pennsylvania-----	8, 84, 147-148
Lake Chabot, Calif.-----	8, 152	Philippine Islands-----	103
Lake Concord, N. C.-----	127	Pinole Reservoir, Calif.-----	152
Lake Dallas, Tex.-----	118	Ponds-----	141
Lake Decatur, Ill.-----	117, 149		
Lake Erie, India-----	79, 105		
Lake Halbert, Tex.-----	36-37		

	Page		Page
Powerlines, erosion of rights-of-way	118, 125-126	Sluicing—Continued.	
Puentes Dam, Spain	27, 101	with mechanical agitation	110-113
Quarrying	127	with hydraulic agitation	110-113
Qued-Fodda Dam, Algeria	27	Smelters, effects from fumes	127
Railroads, erosion of rights-of-way	118, 125-126	Soil Conservation Act	154
Reading, Pa	8, 84, 148	Soil conservation districts	154
Reforestation	147-153	South America	57, 67
Reservoirs—		South Carolina	21
cost in United States	3-6		67-69, 70-71, 74, 118, 125
design of	24-25	Spain	27, 82, 99, 100-102, 112
distribution in United States	4	Spud, description and use	10-12
flood-control	6, 18-19	Storage—	
history of	3	effective	19
irrigation	5, 18, 24	usable	19
navigation	24	Streambanks, erosion and control of	115-
off-channel	51-58		116, 142-144
power	5, 14-16, 21, 23, 93	Strip cropping	136
recreation	6, 19, 24	Suspended-load, records of	22-23
sites, selection of	22-24	Sweetwater Reservoir, Calif	8
surveys, methods of	8-14	South Africa	61, 74-76, 87
water-supply	5, 17	Switzerland	22, 63
Rio Grande, N. Mex	9, 27, 29, 49-50, 66, 116	Takoma desilting works, Wash	57
Rio Puerco, N. Mex	50, 116	Tallahatchie River, Miss	28, 115, 125
Roads, erosion of	115	Tamarisk, effect on silting control	48-51
Roosevelt Reservoir, Ariz	8, 18	Tarkio Creek, Iowa	117
		Tennessee	28, 68, 128
St. Denis du Sig Reservoir, Algeria	111	Tennessee Valley Authority	28, 153, 157
Salt Lake Valley, Utah	41, 152	Terracing, use in erosion control	137-138
Salt River Ariz	8, 18, 106	Texas	8, 19-21, 25-27, 36-37, 50, 52-53, 88-89, 97, 118, 150-151
San Carlos Reservoir, Ariz	8, 18, 27, 30, 58, 62-63, 86, 93, 107-109	Trinity River, Tex	19, 20, 25
San Dimas Reservoir, Calif	84	Underflow	65
San Gabriel No. 2 Reservoir, Calif	95	Undersluices	77-81, 99
San Leandro Reservoir, Calif	152	Union of South Africa	61, 74-76, 87
San Pablo Reservoir, Calif	152, 153	Union of Soviet Socialist Republics	92
Santa Anita Reservoir, Calif	95-96	Upper San Fernando Reservoir, Calif	108
Sardis Reservoir, Miss	28	Vaal River Dam, South Africa	75-76
Sautet Dam, France	27	Val de Inferno Dam, Spain	102
Scranton, Pa	148	Vegetative screens	48-51
Sediment—		Vermont	144, 147
deposition control	64-83	Vernon Hooper Dam, South Africa	61
inflow control	32	Villar Reservoir, Spain	101
production rates	25-27	Virginia	96
removal	83-113	Wappapello Reservoir, Mo	28
sources	114-118	Washington	34, 41, 56-57
trapped, percent	22	Washington, D. C	53
Sedimentation basins	32-47, 51	Washington Mills Reservoir, Va	96-97
Settling basins	32-47, 51	Waste-water release control	74
Shorelines, protection of	146	Water spreading	145
Sierra Madre Dam, Calif	84	White Rock Lake, Tex	SS-89, 93
Silting—		Wildlife planting for erosion control	146
cause of	6-7	Williams Bridge Reservoir, Pa	148
control methods	21	Wilson Dam, Ala	68
damage, magnitude of	19-21	Wisconsin	117
rates of	25-27	Wyoming	103
Sluice gates	78, 79	York City Reservoir, Pa	148
Sluicing—		Zuni Reservoir, N. Mex	34,
flood	98-106		39-40, 103, 142, 152
with controlled water	106-110		

